PROPERTY DEVELOPMENT IN AS-CAST HEAVY SECTION SG IRON CASTINGS BY ALLOYING WITH NICKEL AND COPPER

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CERTIFICATE

This is to certify that the thesis entitled, "Property development in as-cast heavy section SG iron castings by alloying with nickel and copper.", submitted by **Mr. Susanta Kumar Swain** (Roll No: 509MM102) in partial fulfilment of the requirements for the award of Doctor of Philosophy in Metallurgical & Materials Engineering to the National Institute of Technology, Rourkela is a record of bonafide research work carried out by him under my supervision. In my opinion, the work fulfils the requirements for which it is being submitted. To the best of my knowledge, the work incorporated in this thesis has not been submitted elsewhere for the award of any degree.

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Dedicated to

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ABBREVIATIONS

SGI	Spheroidal Graphite Iron
DI	Ductile Iron
DIC	Ductile Iron Casting
MMCs	Metal Matrix Composites
BDT	Brittle-Ductile-Transition
SEM	Scanning Electron Microscopy
DSR	Ductile Shear Regime
BCR	Brittle Cracking Regime
GWEC	Global Wind Energy Council
FEA	Finite Element Analysis
NCMS	National Centre for Manufacturing Sciences
BCC	Body Centred Cubic
ADI	Austempered Ductile Iron
FCC	Face Centred Cubic
DEM	Dynamic Elastic Modulus
UTS	Ultimate Tensile Strength

YS	Yield Strength
BID	Brinell Indentation diameter
BHN	Brinell Hardness Number
ANSI	American National Standards Institute
AWWA	American Water Works Association
ASTM	American Society of Testing and Materials
UTM	Universal Testing Machine
GFN	Grain Fineness Number
GD	Grain Distribution
LOI	Loss of Ignition
ADV	Acid Demand Value
UOM	Unit of Measurement
CE	Carbon Equivalent
EL	Elongation
DBTT	Ductile to brittle transition temperature

ABSTRACT

Ever since its discovery in 1948, the application of ductile cast iron [also known as spheroidal graphite iron (SGI)] has been increasing day by day. This is due to the fact that the material exhibits an excellent combination of tensile strength, ductility, toughness in addition to castability, machinability and damping characteristics. It has also got considerable amount of resistance to corrosion. For these reason extensive works are being carried out now-a-days to produce ductile irons with enhanced mechanical and physical properties. An investigation was performed to improve the mechanical property of thick-walled/heavy section ductile iron castings in as-cast condition alloying with nickel and copper. The property enhancement can be done by heat treatment procedures or by the addition of suitable alloying elements. In the present work, effect of two important alloying elements Copper (Cu) and Nickel (Ni) has been studied in thick section (≥20mm) ductile iron castings. For this purpose fifteen different melts of SG iron were produced in a coreless medium frequency induction furnace having a capacity of 1000 kg. Five of them were almost without nickel and copper (they were present in a very little amount), five were with significant amount of Ni and another five were with significant amount of Cu. Different tests were performed to determine the different important mechanical properties like strength, ductility, toughness and hardness of the matrix structures of each of the melts in order to study the effect of the two alloying elements on those properties. The microstructures of all the different alloys were studied and a phase analysis was performed to get an idea about the structure - property relationship. The results showed that the small addition of Ni and Cu changed the as-cast mechanical properties owing to the different as-cast matrix micro-structures. The study of the tensile properties for the melts without Ni & Cu showed the low strength and hardness as well as high ductility and impact energy with feritic matrix. Some fractions of pearlitic structures were developed near the austenitic cell boundaries due to the presence of Ni in the melts with nickel content. The amount of pearlite increased with increase in Ni content but ferritic matrix rapidly changed to pearlite (for the melts with Cu content) due to the addition of Cu in the melt. The tensile properties for the melts C1 to C5 showed that 0.2% YS, tensile strength were increased with increasing the pearlite level in the matrix structure. The Brinell hardness value for all melts was found increasing from 126 to 252 due to increase in the pearlite content in the matrix as investigated. This change in hardness value reflects the change in the mechanical properties of as-cast heavy section SG iron castings.

Chapter 1

INTRODUCTION

1.1 Purpose of this Research

Ductile iron also referred to as nodular iron or Spheroidal Graphite Iron (SGI) was patented in 1948. After a decade of intensive development work in the 1950s, ductile iron had a phenomenal increase in use as engineering material during 1960s and the rapid use in commercial applications continues today. After the investigation carried out at the Laboratory of British Cast Iron Research Association about the mechanism of the graphite formation in cast iron, a method by which cast irons, having nodular structures in the as-cast state can be obtained without any heat-treatment process was developed [1-2].

The use of ductile iron casting (DIC) has been increasing constantly all over the world. In the recent years there has been increasing interest in solidification of both thin and thick wall ductile iron casting. Most of the work on this subject has been based on metallurgical examination after solidification and cooling to room temperature, which also involves a phase transformation during cooling process. The microstructure of typical commercial spheroidal graphite irons in as cast condition consists of graphite nodules embedded in a ferrite shell and of pearlite. This is the so called bull's eye structure. For determining mechanical properties, the control of microstructural constituents is of practical importance. Since its discovery in 1943, it was observed that the addition of magnesium before pouring transformed the graphite in-to spheroids rather than flakes. This resulted in a new engineering material with excellent tensile strength and ductility. In many industrial applications, this material has replaced existing steel castings or forgings due to its unique properties and achievable cost savings [3-4].

"Iron seemeth a simple metal but in its nature are many mysteries". This statement made by Joseph and Glanville is still true after three hundred years of progress in science and technology. Knowledge is certainly preferable to speculation and yet the approach towards solving a given practical problem will be confusing and haphazard without the guidance of ideas on at least what may take place during solidification. Willing or not, one must depend in part on hypothesis. The independent studies in England at the British Cast Iron Research Association using cerium additions and in the United States at the International Nickel Company using magnesium additions demonstrated the dramatic effect of these elements on promoting the formation of a spheroid, rather than a flake graphite morphology developed during solidification is the key factor responsible for the unique mechanical and physical properties of ductile iron. The use of ductile iron has been increased constantly since its introduction in the market in the 1950s, due to its excellent mechanical properties and low production costs. The main properties are:

1. It is easy to cast (the high fluidity of the metal in its molten state makes it easy for casting process)
2. Tensile strength (strength can be increased to 900N/mm^2 followed by certain practices)
3. Ductility (elongation can increased to more than 20%)
4. Excellent corrosion resistance (when compared to other ferrous metals)
5. Ease of machining (presence of free graphite in the structure lends itself to machining) and,
6. Cost per unit strength (cheaper than most materials) [3-5].

In the spheroidal graphite iron, the graphite nodules are small and constitute only small areas of weakness in a steel-like matrix. Because of this, the mechanical properties of ductile irons are related directly to the strength and ductility of the matrix present-as in the case of steels. The graphite occupies about 10-15% of the total material volume [Fig.1.10] and because graphite has negligible tensile strength, the main effect of its presence is to reduce the effective cross-sectional area, which means that ductile iron has tensile strength, modulus of elasticity and impact strength proportionally lower than that of a carbon steel of otherwise similar matrix structure. The matrix of ductile irons can be varied from a soft and ductile ferritic structure, through harder and higher strength pearlitic structures to a hard, higher and comparatively tough tempered martensitic or bainitic structure. Thus, a wide range of combinations of strength and ductility can be achieved. General engineering grades of ductile iron commonly have the structures which are ferritic, ferritic/pearlitic or pearlitic. Controlled processing of the molten iron precipitates graphite as spheroids rather than flakes. The round shape of the graphite eliminates the material’s tendency to crack and helps prevent cracks from spreading. As far as the mechanical properties are concerned, the graphite morphology for flake graphite and spheroidal graphite plays an important role. The flake graphite as found in gray irons, possesses its unique properties viz., detrimental to its mechanical strength, breaking up the continuity of the metallic matrix & reducing ductility. The sharp edge of the flake acts as stress raisers and further reduces the strength. This type problem is not found in SG iron. The graphites are in discrete spheres giving rise to continuity in the metal matrix therefore allowing ductility [4-6].

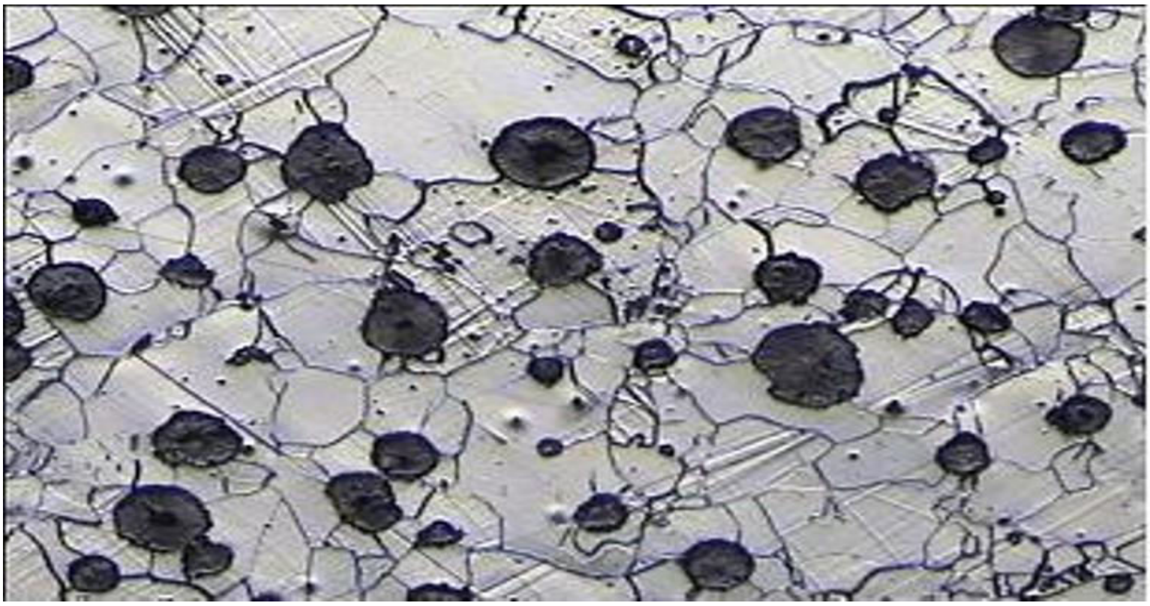


Fig.1.10. Graphite nodules embedded in the ferritic matrix (Source: Self research work)

The alloy first undergoes the stable eutectoid reaction in which austenite decomposes to give ferrite and graphite. Ferrite nucleated at the graphite/austenite interface and then grows symmetrically around the nodules. This reaction is called the ferritic reaction. This growth is controlled by diffusion of carbon through the ferrite shell, which makes it quite a slow process. Therefore the temperature of the metastable eutectoid could be reached before the complete transformation of austenite. Once the metastable reaction is initiated, it proceeds quickly because of the co-operative growth of ferrite and bainite. This latter transformation is similar to the pearlitic reaction. The different grades of SG irons are produced by controlling the matrix structure around the graphite either simply by changing casting parameters or by subsequent standard heat treatment practices. Alloy additions may be made to ductile iron with a view to control the matrix structure (as-cast) and strength, the mechanical properties in order to provide response to heat treatment. Special analysis of ductile irons and high alloy ductile irons can provide unusual properties for special applications. [5-7].

Ever since its discovery, ductile Iron has been identified rapidly as the right material for many wind mill parts, its major advantages over steel being higher castability, lower density, improved machinability, design flexibility, while offering the required mechanical properties. Although some pearlitic and ADI castings are used for certain parts (e.g. gears), most of the Ductile Iron components found in wind energy turbines satisfy the stringent ENG-GJS-400-18-LT specification. When compared to steel castings, Ductile Iron offers weight reduction and can meet the mechanical requirements of many wind mill parts (tensile strength, impact energy, fatigue strength) without heat treatment. Indeed, low Mn, low P, low Si ferritic Ductile Iron, produced under carefully controlled parameters, exceeds the targeted properties in the as-cast condition. In recent years, there has been a clear tendency towards weight reduction (high strength to weight ratio) on manufacturing of components for automobile industry in order to reduce costs & higher fatigue life. In the case of transport industry, certain steps are being taken to manufacture automobile parts as to compile the environmental issues [6-7].

In a global world always requiring more energy but becoming highly conscious about the environment and the effect of human activities on it, renewable sources of energy have become an unavoidable choice for industrial countries and amongst these renewable sources of energy, wind energy has gained general acceptance. As shown in Figure 1.11, more than 8,000 MW were installed in 2003 worldwide, and this value is expected to continue to increase steadily in the coming decade. Although development of wind energy was initially concentrated in Europe, it now takes place in all regions of the world. From a recent study, it is found that there is a total of 51.477 MW installed globally during the 2014 period. The wind industry set a target to achieve this one after slowdown in 2013. Annual wind energy installation capacity in region wise is shown in figure 1.12.

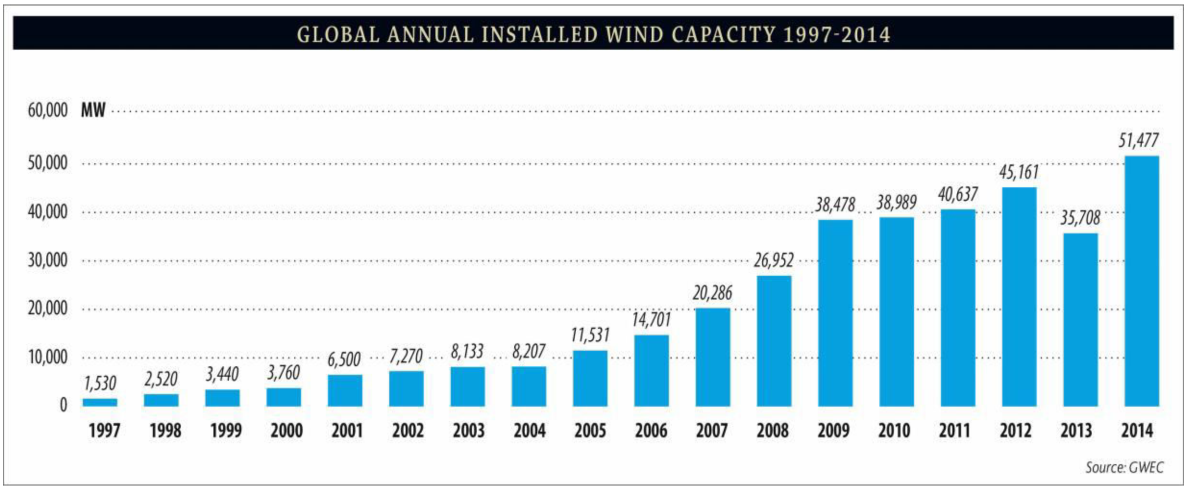


Fig. 1.11 Global Annual Installed wind Capacity,1997-2014, Source: GWEC (Global wind energy council, http://www.gwec.net/global-figures/graphs/ dt.05/03/215)

Considering the development of mechanical properties of SGI castings in as-cast condition, the present efforts have been focused on control of processing variables (pouring temperature, pre-conditioning of base iron, inoculation practice, moulding materials and the quality of materials used for casting process) in different stages during tapping and pouring of metal. Several studies were carried out in order to improve the production process of spheroidal graphite iron and to identify the characteristics of the microstructure and the final mechanical properties. The present investigation also focused on the results of microstructural characterization and enhancement of mechanical properties of thick wall ductile iron castings.

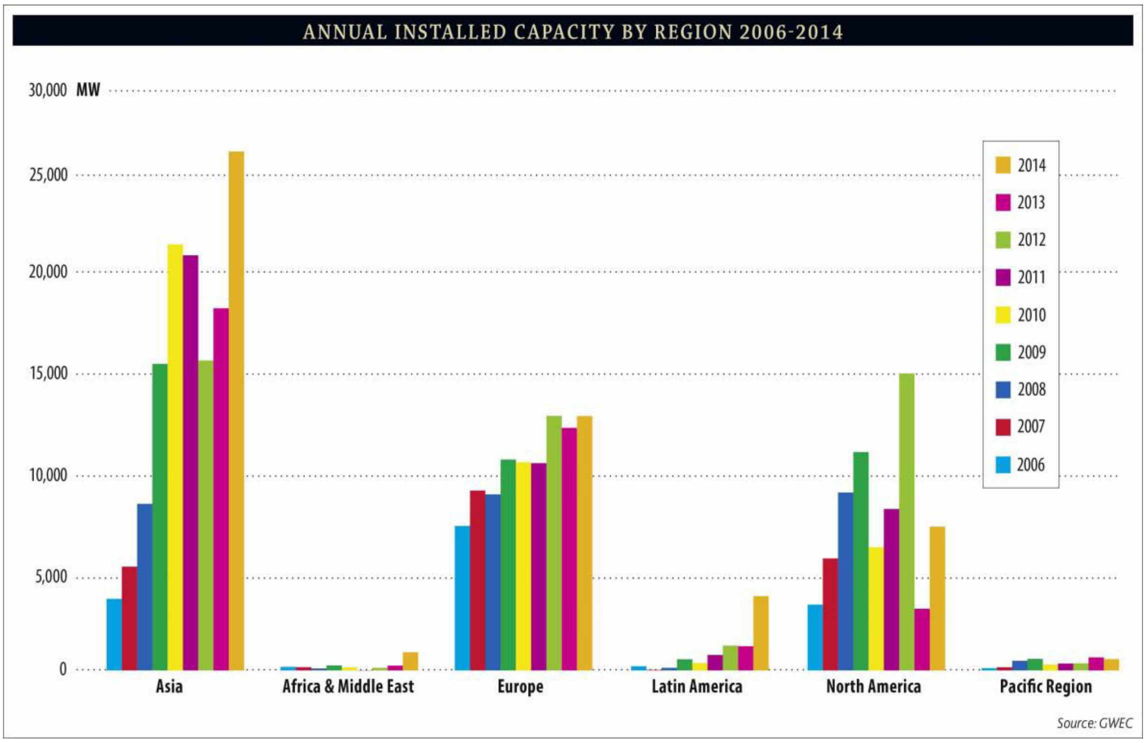


Fig.1.12 Global Annual Installed wind Capacity, region wise 2006-2014, Source: GWEC (Global wind energy council, http://www.gwec.net/global-figures/graphs dt.05/03/215)

We know that the production of ferrous castings predates biblical times, but there was very slow advances in the art were made over the several thousands of years Involved. The science of metallurgy played major role for the significant advances production of ductile iron around the start of the 20th century and really the curve turned upward. The metallurgists then investigated seriously to study the effect of variations in composition, melting and casting procedures, solidification characteristics, cooling rates, processing variables and many other parameters involved in the foundry processes. Effects were being made to correlate strength to size of graphite nodules, amount of nodule count, graphite shape, distribution of graphites in the metallic matrix and methods of influencing these factors were being developed. However, the technical literature were completely silent regarding i) a cast iron having it's graphite in the spheroidal form in the as-cast condition or ii) a high carbon of any type exhibiting ductility in the as-cast condition.

The present research work thus is undertaken to study the property development in as-cast heavy section SG iron castings by alloying with nickel and copper. The quality of raw material used for the SG iron production and the compressive strength of the furan resign sand used for the mould preparation was monitored to meet the best standard foundry practices A clear look was made on the chemistry of the mould and solidification of the casting to get desired properties in as-cast condition. Attempts have also been made to characterise the graphite morphology in order to correlate with the results obtained.

1.2 Scope of the Experimental Work

Ductile iron as a technologically useful material has been employed for a score of years. During this period while many investigators have examined its mechanical performance under a wide range of conditions, others have attempted to explain its solidification behaviour and the many variables which intervene in producing an acceptable product. Yet even at this date we are still at a loss to explain in a fundamental way how an otherwise flake like graphite shape develops in to spheroidal morphology which gives ductile iron its superior properties. Gray iron foundries have been in existence for many centuries. Gray iron was found to be brittle and could not stand high stresses especially under shock loads. In 1722 production of malleable cast irons started. It was first developed by Reaumer. This material had adequate strength and could resist shocks. But malleablising process was found to be tedious. Metallurgists continued unabated research to find high strength irons. It was understood by metallurgists that the quantity, shape, size and distribution of Graphite in Cast Irons were the most important features to be controlled to get superior properties. Research, therefore, continued to develop a method to control shape, size and morphology of the graphite [6-7, 21]. It was found that inoculation with graphitizers and controlled composition of base metal would give superior properties. Ladle inoculation methods were developed. One of the earliest workers in this field was by Wust. In 1908 Gielenkirchen pointed out that ladle addition may be supplemented by calcium and vanadium. He suggested that Mg can be added as Mg – Al alloy or Mg – Ni alloy and indicated that Mg gave good results. In 1917 Portbuin and Lemoine produced inoculated iron by Fe – Si. In 1917 Meehan was granted patent for inoculation with Calcium Silicide. Close controlled melting formed the basis for Meehanite Process. In 1927 Mond Nickel Co patented the addition of Nickel and 80% Fe – Si. The amounts were calculated to provide the elements in equal proportion. High Duty Iron called Ni – Tensile was produced. German workers produced useful cast irons by using Fe – Si. Proprietary inoculants like SMZ were introduced [7-8].

All these research works produced iron of high strength but none of them was ductile or showed elongation under tensile loads. It was understood that ductility could be produced by proper heat treatment as in the case of malleable iron, where the graphite was found to be in temper carbon type or aggregate type. The prospect of producing this type of graphite in as - cast condition had long been attractive to foundry men and isolated nodules of graphite had been observed in cast irons. This search for obtaining nodular graphite in as- cast condition in cast irons had been going on all over the world. In 1947 BCIRA announced substantial completion of long time Research on graphite formation and published that “Nodular or Spheroidal graphite can be obtained by ladle treatment of suitable iron with Cerium”. The base iron has to confirm to close limits of composition. Simultaneously International Nickel Co announced that a work of similar nature had been carried out in the USA and “S.G”. Irons could be obtained from molten metal treated with Magnesium. High strength and good value of elongation could be obtained by simple annealing treatment”. This opened up a New Era for foundry men [8-9].

In the production of SG iron, the chemical composition, rate of cooling and inoculation practice contribute a major effect on the physical and metallographic properties of SG iron. The role of manganese and copper has a significant effect on the mechanical and metallographic properties of the ductile iron. The decomposition of austenite to ferrite plus graphite or to pearlite in spheroidal graphite (SG) cast iron is known to depend on a number of factors among which are the nodule count, the cooling rate and the alloying additions (Si, Mn, Cu, etc.). The microstructure of typical commercial spheroidal graphite (SG) irons in as-cast state or after heat treatment consists of graphite nodules embedded in a ferrite shell or other constituents like pearlite. The mechanical properties of ductile irons are related directly to the graphite morphology. The number of graphite particles present in a specific unit area of a metal is called nodule count. Generally, the quantity of nodules present in a one square milimeter area of a polished specimen when viewed in 100X optical microscope. Nodule counts determine the quality of iron. An optimum nodule count is required for better mechanical properties. It is also known that with increase in section thickness, the nodule count decreases. For years, sulphur and manganese have been known to play significant roles in gray iron chemistry [9-10].

A number of studies attempting to explain the effects of these two elements in terms of manganese level, sulphur level or manganese to sulphur ratio in the iron have led to some confusion as to the exact effect these two elements have on the metallurgy of gray iron. The effects of two elements on the microstructure & properties often a gray iron has been attributed to the presence (or absence) of manganese sulphide formation. When both manganese and sulphur are dissolved as a solution in liquid iron at a particular temperature, they satisfy the equilibrium relation with manganese sulphide, as follows (Eqn. 1):

$Mn_{(in\ soln)}+S_{(in\ soln)}=MnS$........ (1)

A similar relation can be made for the equilibrium between iron and sulphur (Eqn. 2)

$Fe_{(liq)}+S_{(insoln)}=FeS$............... (2)

From both the equations, it is found that (Eqn.3)

$Mn_{(in\ soln)}+FeS=Fe_{(liq)}+MnS$.... (3)

The stoichiometric amount of Mn required combine with the sulphur is 1.7 (%S). This means that the ratio of manganese to sulphur in a manganese sulphide particle is 1.7. To assure that all sulphur present in gray iron forms manganese sulphide, another formula (Eqn.4) has evolved throughout the industry: Mn% = 1.7 (S %) + 0.3 %......(4)

The investigations sought to apply these findings to actual thick walled ductile iron castings. There is a scope to study different processing variables and the melt chemistry with microstructural changes during solidification. A correlation has to be made between graphite morphology and mechanical properties. The dependant of mechanical properties on graphite spheroids, size of the nodules and nodule counts is an interest of study in as-cast condition. Therefore, a series of melts of SG iron containing varying amounts of copper and manganese with monitoring the processing variables will be cast as Y blocks at several metal casting facilities. Each block is to be examined for its mechanical properties and microstructural analysis. Some samples of varying content of copper and manganese are also taken and microstructural characterization was performed. The melt chemistry and the cooling rate are also having impact on mechanical properties of ductile iron.

1.3 Background & Motivation

The presence of graphite in nodular form was found to be the key factor responsible for the unique mechanical and physical properties of ductile iron [10]. The use of ductile iron has been increasing constantly since its introduction in the market in the 1950s, due to its excellent mechanical properties and low production costs [11].

Ductile iron is defined as a high carbon containing iron based alloy in which the graphite is present in compact, spherical shapes rather than in the shape of flakes. Its chemical composition and percent of carbon is nearly the same as grey iron. The transformation to ductile iron occurs when molten grey iron is treated with magnesium. The insertion of magnesium in to the pouring ladle transforms the graphite flakes into spheroids. These spheroids strengthen the metal by acting as crack arresters instead of crack assistors [12]. Considering its properties, it is easy to cast having better strength and ductility, excellent corrosion resistance, ease of machining and cost per unit strength. The microstructure of commercial SG irons in as-cast state or after heat treatment consists of graphite nodules (Figure 1.10) embedded in a ferrite shell or in a pearlitic matrix. This is so called bull's eye structure [13]. The control of this microstructure is of practical importance because it determines the mechanical properties of SG irons. Reducing the weight of ductile iron castings is an important method for saving energy and materials. For example, in case of an automobile a reduction of 100 kg in weight reduces the petrol consumption by 0.5 litres per 100 km journey [14]. So many metallurgical workers are dedicating themselves for developing and perfecting thin section ductile iron casting technology [15].

Now-a-days, SG iron castings play vital role in producing different automotive equipments and also in wind mill parts. The best method is to produce SG iron with ferritic matrix. This can be followed during casting process or adopting additional heat treatment which aims to convert pearlite into ferrite and graphite [16]. Even different ferritic structures castings may differ in some mechanical characteristics. This present investigation also aims to study the microstructural behaviour of as-cast SG irons. The fracture toughness is increased if surface area to volume ratio of the spheroid is low and hence crack propagation is reduced. It is also known that SG iron is a good conductor of heat and increases the resistance to fire-cracks by reducing the locally induced thermal stress. The impact resistance is also superior to that of flake graphite iron. Hence, impact resistance property of as-cast SG iron has been checked thoroughly at different temperatures in the scope of this study.

The influences of mechanical properties of SG irons are also due to chemical heterogeneities which build up during solidifications of cast irons at the scale of microsegregations [17]. Since aspect ratio plays an important role in establishing the mechanical properties of SG iron, effect of chemistry should also be a part of the investigation as aspect ratio is fully influenced by chemical composition of the SG iron in as-cast condition. The size of the graphite nodules affects both mechanical and physical properties. So, microstructural analysis has been taken as a key factor in this study. During the course of literature survey, the alloying elements play vital role during decomposition of austenite to ferrite and graphite or to pearlite in SG iron. The roles of different alloying elements with different weight percentage have been analysed [13].

Spheroidal graphite (SG) irons are very unique materials used in different engineering applications due to its good castability and mechanical properties. All most all members of SG irons posses graphite in the form of spheroids with different matrix structures [26], but the mechanical properties are directly related to the matrix, nodule count, nodule size and aspect ratio. There are many variables like chemical composition, cooling type, post inoculation, amount of residual magnesium and pouring temperature responsible for structural control of SG iron. The microstructural analysis has been performed with the help of Image Analyzer. As compared to low carbon steel, graphite spheroids in a ferritic matrix exhibits good ductility, impact resistance, and good tensile and yield strength. During the last decades, the production of spheroidal graphite iron has witnessed a continuous expansion due to the improvement in mechanical properties as well as in graphite morphology by adopting adequate casting technology. On the other hand, the microstructure can be conveniently modified by using a wide range of heat treatments, such as normalizing, ferritizing, quenching and tempering, and austempering to achieve ferritic, pearlitic, martensitic and ausferritic matrices respectively. Researchers and producers continue their search by applying standard foundry practices for new SG iron applications. The safety for critical parts is one of their main targets [72].

The mechanism of the formation of the graphite spheroids in cast iron, as an alternative to the flake variety, has been studied extensively and intensively ever since the first detailed observations were published in the 1940s. Despite the considerable efforts made by large numbers of researchers and improved casting technology, there is still a disagreement on the importance and necessity of heterogeneous nucleation of the graphite in one hand and, on the other hand, the dependence on preferred growth in the c-axis direction as compared to the a-axes directions of the graphite[73]. Graphite in the spheroidal form can be obtained in the quasi-ferritic state after casting. However, the casting is subjected to a ferritization heat treatment in order to increase its ductility by eliminating the limited fraction of brittle pearlite, which may exist in the as-cast state [74]. So in this work, the main aim is to produce spheroidal graphite iron in as-cast condition, with taking care of all processing variables.

It is well known that silicon inhibits ductile to brittle transition temperature of SG iron. Castings should have low silicon content that is required to achieve good impact properties at sub-zero temperature. The proof stress of SG iron also influenced by the presence of silicon in the casting. The change in proof stress due to the influence of Si may be up to 80N/mm^2. The adequate sub-zero impact resistance property increases with addition of 1% silicon, but can undesirably result in low tensile values. So many foundries have reduced silicon content to less than 2% and alloyed with nickel or copper to maintain adequate proof stress [18]. Different weight percentage of nickel and copper has been added during melting to get desired property in this work.

The mechanical properties obtained from SG iron castings are adequate for a wide range of applications in wind mill parts and automotive industry. So, nickel addition is sometimes made when a higher proof stress is required or small amount of Tin is used to get fully pearlitic matrix structure. In addition to the mechanical properties, a number of other characteristics such as density, thermal expansion, thermal conductivity, specific heat, electrical conductivity, magnetic properties and acoustic properties are of considerable significance. These properties are referred to as physical properties. The thermal conductivity property of SG iron is also influenced by the graphite growth direction. The influence of different microstructural constituents and effect of different local conditions are also key points of discussion in the present investigation.

The formation of graphite spheroids has been studied extensively and intensively ever since the first detailed observations were published. Despite of different evidence by many researchers, there is still disagreement about the importance and necessity of heterogeneous nucleation of the graphite and also the dependence on preferred growth in the c-axis direction as compared with the a-axis direction of the graphite [73]. From time to time, many researchers have drawn conclusions on the basis of their knowledge and experience regarding the formation of graphite spheroids in the ferritic matrix. It is a matter of interest to understand in detail about the actual mechanism and phenomenon by considering the following parameters.

- Radial orientation of the crystallites
- Preferential c-axis growth
- Heterogeneous nucleation mechanism and its relation to radial orientation and c-axis growth
- Homogeneous nucleation
- Chemistry of the iron and presence of inclusions
- Effects of inoculation
- Bending of crystals
- Branching and curvature of growth crystals
- Initiation of monolayer spheroids

So, it is a matter of interest and motivation to study graphite morphology and its formation during solidification in as-cast condition. A number of samples have been studied under Image Analyzer to correlate the observations with standard ASTM structures. Over the last few years, a number of thermal process have been introduced for changing the matrix as well as graphite morphology of ductile iron for getting better mechanical properties. The treatment of austenitizing together with austempering and quenching leads to the enhancement of mechanical properties. But in as-cast condition, the property may be increased by controlling different parameters during metal processing and process control which is a matter of discussion in the present study.

1.4 Novelty of the present work

From the literature survey, it was found that most of the work done so far on the property development of SG iron by alloying with different alloying elements or adopting different heat treatment process. Based on this survey, An investigation was made to produce and to improve the mechanical properties of thick-walled ductile iron castings (75mm) by alloying with Ni and Cu in as-cast condition, The present work provides some significant studies on:

1. The effect of addition of different weight percentage of Ni and Cu on the mechanical properties (viz., tensile strength, 0.2% YS, Ductility, hardness and Charpy impact strength at -20^{o}C).
2. The role of section size for the property characterization of SG iron castings in as-cast condition.
3. Study of microstructural analysis and the graphite morphology of the castings produced in as-cast condition for better understanding of structure-property relation.
4. As the topic is focused to direct importance to industry, the melt chemistry is very carefully monitored to get the expected results as more percentage addition of nickel or copper creates adverse effects on the tensile properties.
5. The furan resin sand mould and the late inoculation practice adopted in the present investigation is original and the results obtained are interesting.
6. Nodule count, nodularity and the matrix structure also studied in the present study and its impact on the mechanical properties are also analysed.
7. The best combination in chemical composition is recommended as per the requirement of desired results for the production of thick-walled SG iron castings used for different industrial applications.

Chapter 2

2. Aims and Objectives

Spheroidal graphite iron is defined as a high carbon containing, iron based alloy in which the graphite is present in compact, spherical shapes rather than in the shape of flakes, the latter being typical of gray cast iron. After three hundred years of progress, the above words of Joseph Glanville are still true. Knowledge is certainly preferable to speculation. And yet, the approach towards solving a given practical problem will be confusing and haphazard without the guidance of ideas on at least what may take place during solidification. Willing or not, one must depend, in part, on hypotheses.

The matrix of ductile irons can be varied from a soft and ductile ferritic structure, through harder and higher strength pearlitic structures to a hard, higher and comparatively tough tempered martensitic or bainitic structure. Thus, a wide range of combinations of strength and ductility can be achieved. General engineering grades of ductile iron commonly have the ferritic, ferrito-pearlitic or pearlitic matrix.

With the exception of silicon, all elements promote pearlite and all elements with the exception of silicon, nickel and copper also promotes carbides. The strength properties of ferritic ductile iron are generally increased by the elements, which go in to the solution. With the exception of carbon, all the elements increase tensile strength and hardness.

A 1% addition of silicon raises the proof and tensile strength of a ferritic iron by approximately 82 N/mm^2 whereas 1% of nickel increases these properties by 46 N/mm^2. In the ferritic irons increase in tensile strength and proof strength are obtained at the expense of ductility and in such case the iron can become embrittled. Ductile iron castings are more prone to contain carbides than flake-graphite castings of similar section and size and carbon and silicon contents. This is partly due to the fact that both the spherodizing elements (Mg and Ce) promote the formation of eutectic carbide and partly because of sequence of solidification produced by the growth of graphite nodules. The growth of nodules causes under cooling during solidification to temperatures at which white iron structure as likely to form. Carbides in ductile irons can occur in three forms:

Eutectic carbide (or chill) results mainly from the rapid solidification and is most prevalent in corners and thin sections. Inadequate inoculation, low carbon and in particular low silicon and the presence of carbide promoting elements increases the likelihood of carbides being present in the structure.

Inverse chill, which has fine acicular form, occurs at or near the heat centre of a casting section. The geometry of the casting and method of running the casting are important variables and the problem is often only solved by re-positioning or altering the size of ingates to change the pattern of solidification of casting.

Segregation of carbides is more prevalent in heavy sections. They occur in the eutectic cell boundary area where the segregation of trace amounts of carbide forming elements such as manganese or chromium occurs. These carbides do not readily respond to break down by heat treatment. The presence of carbide in ductile iron is undesirable for a number of reasons:

- It increases the tendency to form shrinkage porosity and thus increases the feeding requirements during casting.
- It increases the risk of cracking during knockout and fettling.
- It decreases the ductility of the iron.

- It drastically reduces the impact resistance.
- It increases hardness and reduces machinability.
- It requires heat treatment to 900-920^oC to remove the carbide.

The occurrence of all the three forms of carbide is minimized by efficient inoculation giving high nodule number and also by maintaining the contents of carbide promoting elements at low level. High silicon levels are also beneficial but the potential embrittling action of silicon contents particularly when it is above 2.6 wt% should be kept in mind.

Objectives of the Present work:

An exhaustive literature survey as summarized in the thesis has helped to set the objectives of this research work which are outlined as follows:

- Preparation of SG iron in a medium frquency induction furnace by melting and casting process as per standard foundry practices.
- To improve the mechanical properties of thick-walled ductile iron castings by adding different weight percentage of Nickel and Copper in as-cast condition.
- Research work is to be carried out for thick-walled (75mm) castings in as-cast condition.
- Efforts have to be made on control of processing variables (pouring temperature, pre-conditioning of base iron, inoculation practice, molding materials and the quality of materials used in casting process) in different stages during tapping and pouring of metal.
- There is a scope to study different processing variables and the melt chemistry with microstructural changes during solidification.
- Evaluation of mechanical properties of SG irons without Cu & Ni, with copper and with nickel, and comparision of the results with the graphite morphology, nodularity and nodule counts.
- Study of microstructure in order to correlate the structure-property characteristics.

Hence an attempt has been made in the present study to improve the mechanical properties of thick-walled ductile iron castings with the addition of different weight percentage of nickel and copper and controlling the process parameters, following standard foundry practices, using good quality of raw materials and furan resin sand moulds under the topic “Property development in as-cast heavy section SG iron castings by alloying with nickel and copper”. To achieve the desired result, the present work was started with the following objectives:

2.1 Possibly effective steps to improve the strength through alloy addition

This objective has the following sub headings.

- Carbon and Silicon are directly involved in the formation of graphite nodule. So these elements should be high in the metal composition. As Phosphorus act to decrease the strength, we have to decrease the Phosphorus in the composition that can be done by proper selection of the charge material mainly the pig iron. The Phosphorus percentage should be is less than 0.03 wt% with high C and Si content.
- The graphite nodules depend upon the percentage of Carbon, Silicon and oxygen present in the metal composition. We can control the C, Si content by proper charge mixing and also the addition of coke and Ferro silicon when required but there can’t be any direct control over oxygen. Indirect control is possible by avoiding heating over 1480^{o}C.We have to avoid over treatment with Mg. Normally oxygen content in ductile iron is 20 – 50 ppm or 0.002 - 0.005 % due to the overheating or longer duration of heating the oxygen comes out in the form of oxides like as carbon-dioxide, silicon-dioxide due to which the nodular counts decrease.
- Due to the high superheating of the metal more time will be required to change the state from liquid to solid .Due to this longer cooling time the chances of large nodule

formation of the graphite is high and decreased the strength so the tapping temp should not be so high.

- Addition of nickel and copper in different melts will be carried out in specific time interval during melt preparation in order to get desired melt chemistry as per standard foundry practices.

2.2 Temperature calculation according to the composition

To control the tapping and pouring temperature of the SG iron melts, the following practice has been followed during entire casting process.

Pouring Temperature = 1540^{o}C – (Total depression) + superheat temperature

Tapping Temperature = Pouring temperature + 50^{0}C.

2.3 Inoculation practice

The best process of inoculation for SG iron inoculation treatment after the Mg treatment completes. Instream inoculation is also effective in SG iron production. In the present study, both instream and ladle inoculation has been performed. The inoculants is directly mixed with the metal stream during pouring of the metal. Proper grain size is essential for this process. In case of addition of inoculants in the ladle during tapping process, proper size of the inoculants are added in the 1/3 metal stream during tapping when the Mg treatment is already completed.

2.4 Effect of time and temperature on inoculation

The effectiveness of the inoculants is highly influenced by the metal temperature during addition and also by the time after melting. The efficiency of inoculants decreases with pouring time interval. It also decreases when the temperature is very high. The inoculants have direct effect on the nodule counts and the nodularity of the graphite

2.41 Nodular count

The number of nodule per unit area changes the strength as the nodules act as voids in the metal phase when the size of the nodules is larger than the strength on the particular portion decrease than that of other section. So if small size of nodules is formed throughout the section will be stronger than the large nodule section. The quality of the SG iron is determined by nodule count. An optimum nodule count is required for quality castings. The nodule count decrease with increase in section size of the casting. With increase in nodule count, more is the uniformity in the structure-property relation.

2.42 Nodularity

Nodularity is an important factor as far as strength is concerned. In gray iron where graphite is present in the form of flake, the stress concentration takes place at the edges of flakes and strength is reduced.

In SG iron the graphite are present in form of nodules due to which stress concentration does not take place. When the nodules are not perfectly round strength begun to decrease .For the proper strength 95% nodularity is best. The shape will be slightly elliptical when nodularity is 75%. Identification of nodules is a part of nodularity rating, ranging from 0 to 100%. When all nodules are completely of round shape, the state is called 100% rating, irrespective of the actual number of nodules.

Considering the development of mechanical properties of SGI castings in as-cast condition for thick walled ductile iron castings, the present efforts have been focused on control of processing variables (pouring temperature, pre-conditioning of base iron, inoculation practice and moulding materials) in different stages during tapping and pouring of metal, addition of alloying elements like nickel and copper. A correlation between mechanical properties with matrix microstructure has been made.

Chapter 3

3. Literature Survey

The main purpose of the literature survey is to provide background information on the issues to be considered in the thesis and to emphasize the relevance of the present investigation. The knowledge of particular literatures of the past studies is effective for the formulation of sound methodology which acts as driving force during the advancement of any investigation. The new field of research can be inferred from literature. A lot of efforts are being made globally for improving the property in SG iron castings. This treatise embraces various aspects of SG iron castings with special reference to their structure – property characteristics. The review of the literature related to the present study is organised and presented as follows.

3.1 Historical background

During the period 1948-50, research work regarding the investigation of the mechanism of graphite formation in cast iron was conducted at British Cast Iron Research Association (BICRA). This research work led to the development of a method by which cast iron containing graphite nodules (or spheroids) could be developed without any heat treatment procedure [20].

The initial work leading to this discovery was carried out by Morrogh and Williams and recently a detailed account of the development of the process and the theories behind it has been developed. Ordinary gray cast irons have their graphite carbon distributed through the metallic matrix in the form of flakes varying differently with shape and size with respect to chemistry of the molten metal, cooling rate, method of melting, ladle treatment etc. These graphite flakes interrupt the continuity of the metallic matrix and so render the material relatively brittle and non-ductile [1-3].

It is well known that the production of ferrous castings predates biblical times, but very slow advances in the art were made over the several hundreds of years involved. Not until the science of metallurgy began to make significant advances around the start of the 20th century did the curve really turn upward. The metallurgists then seriously began to study the effect of variations in composition, melting procedures, solidification characteristics, cooling rates, processing variables and many other parameters. Efforts were being made to correlate strength to size, amount, shape, distribution of graphite and methods of influencing these factors were being developed. However, the technical literature were completely silent regarding (i) a cast iron having it's graphite in the spheroidal form in the as-cast condition or (ii) a high carbon of any type exhibiting ductility in the as-cast condition.

One of the materials to be born in this era and which was being promoted in the 1930s was an abrasion resistant white cast iron with high hardness which resulted from a martensite-carbide matrix promoted by Ni and Cr contents nominally 4.5% & 1.5% respectively. This material or family of materials still produced in large quantities all over the world for grinding mill balls, plates, rolls and many applications requiring outstanding abrasion resistance. It is a product well known in Australia and very likely will enjoy a sizable growth in view of the huge mining potential. After 2nd world war, Cr appeared to be one of the elements that would become scarce and without it; white cast would be less carbidic, considerably softer and hence lacking in the desired abrasion resistance. To meet such eventually, research laboratories all over the world seek a substitute element of a Cr as a carbide former in martensitic white cast iron. Necessarily, the element have to satisfy all the three conditions i.e. be plentiful on critical to the war effort and be required in small amount .All the metallic and semi metallic elements which were known to combine chemically with carbon to form carbide were tested. Among these was Mg. Further it was believed by the investigators that the solubility of Mg in ferrous materials was exceeding low. The addition of Mg was the sole purpose of deoxidation ,evidently with no desire or hope of retaining in the iron .The addition of Mg to the base iron exhibited unusual toughness by resisting fracture where as other broke in usual brittle manner. An analytical method to determine Mg in cast iron was learnt latter. Now it is known that Mg can be retained in iron in amount more than 1% [12-13, 26].

The next step obviously was to investigate the effect of Mg on simple grey cast iron and such a research programme was started early in 1943. The grey cast iron was treated with various amounts of Mg as 80%, Ni-20% Mg alloy up to a minimum of 0.3%. An examination of microstructure showed that refinement of flake graphite had occurred. The obvious next step was larger addition of Mg. There was much excitement in the laboratory when the heats were tested, for the results lead to the realization that it was not merely an improvement in cast iron that had been achieved, but rather creation of a completely new product .The tensile strength increased to unexpected level. An immediate examination under microscope revealed that the graphite was not present as flake but as well dispersed spheroids. With a small, but effective amount of Mg produced high strength spheroidal graphite cast iron as well as with good mechanical properties.

Generally Spheroidal graphite cast iron is usually produced using Fe-C-Si alloys, in which the chemical composition is so adjusted to guarantee the formation of spheroidal graphite during solidification. The detailed parameters have been investigated for its production for the expanded use of spheroidal graphite cast iron in industry because it posses attractive mechanical properties by casting. However, the basic interpretation regarding the formation and morphology of graphite spheroids is not fully understood even though many theories have been suggested since its invention.

3.2 A New Engineering Material, 1948-50, successful production of Nodular graphite structures in Gray cast irons.

This method was developed by H. Morrogh. He was able to produce nodular graphite structures in grey cast irons. The treatment involved addition of certain amount of cerium in low sulphur hypereutectic cast irons shortly before castings without going for proper heat treatment [20].

The cerium is conveniently added as misch metal and functions first as a desulphurizer & second as a carbide stabilizer. By treatment with cerium, only the hypereutectic graphite becomes nodular and other graphite remains as a new pattern called quasi-flakegraphite. Nodular cast irons with all the graphite in spherulitic form are obtained by treatment of molten metal by certain amount of cerium followed by adding graphitizing inoculants like ferro-silicon or ferro-silicon-magnesium.

Production of nodular graphite structures in the cast irons by the process of H. Morrogh represents a new development in the field of metallurgy of cast irons. Later, new ideas and methods are included in this process and more research has been carried out to find better spheroidal graphite iron in terms of properties and quality to meet the present industrial requirement. Design Engineers can now optimize casting shape and performance with increased speed and confidence. Recent development in CAD/CAM, solid modelling and finite element analysis (FEA) techniques helps to analysis accurately the stress distribution and component deflections under simulated operating conditions [1, 3].

3.3 Different research work & Industrial practices to strengthen the Nodular graphite irons

In due course, many researchers came forward to carry out research work on spheroidal graphite iron to modify production method, volume of production, changing in process for better quality, monitoring all the technical parameters to meet the desired properties and its applications.

J.D.Honser in his working with Chevrolt-Saginaw Nodular iron plant has explained in his article regarding the cost of production and quality of the material. The quality of nodular iron was not affected by producing in arc duplexing furnaces irrespective of the operational parameters monitored. The furnaces are viewed primarily as temperature control devices but their role in controlling chemical analysis and providing a buffer between cupola and pouring line is of highly importance. For production of nodular irons, no adverse effect was found by using this furnace, but while considering the beneficial part, refractory practices are same as in case of arc furnaces but wear is noticeably less than that in a melter as experienced. The need for a high degree of iron control in nodular iron production practices is adequately met by the arc duplexing furnaces with a minimum of effort and at a reasonable cost. Arc duplexing process can be an invaluable tool in nodular iron production practices where close control is mandatory [22].

S.T.Holtan & W.J.Peak has given a remarkable overview on production of nodular iron in basic cupola melting process. This practice generally refers to cupolas operated with neutral to very basic slags. This is the significant method of producing ductile iron by desulphurising during the melting of base iron. Not only sulphur, oxygen is also reduced. Reduction of these two elements substantially reduces the usage of magnesium during treatment. Since magnesium serves first as a deoxidizer & desulphurizer before being an effective nodulizer, the fewer amounts of oxygen and sulphur helps in usage of less amount of magnesium for nodularization. On the other hand, the main disadvantage of this process is high loss in silicon content in the melt as the silicon loss is attributed to the increasing affinity for silicon by the slag as the slag basicity increases. A second disadvantage is that the melting process is lower as compared to an acidic cupola operation. It is due to the increased coke and flux additions made in a basic operation. The main overview of this process is, while basic cupola melting offers some significant advantages in ductile iron productions, it also involves some penalties. Only close monitoring and evaluation can be made whether either of these practices is required or not [23].

T.K.McCluhan has given a revolutionary description and treatment of nodularising materials and methods in his proceedings. Concurrent with the commercial and technical growth of ductile iron, there has been an evolution in the range and character of nodularising materials which offer to foundry men a wide Varity of approaches to the production of ductile iron. He also described the effects of various nodularizing elements for the production of ductile iron with respect to the nodularising elements used in the previous stage. The basic back ground of understanding the elements of nodularizer design and their applications also mentioned in his article. For the production of ductile iron, magnesium and rare earths have been considered as an integral part from its earliest stages. There elements play important role for producing ductile iron and developing nodularizing materials. There are a large number of nodularizing elements now available to meet the needs of ductile iron producer [24].

David Matter has adopted different nodularizing methods for producing ductile iron castings. He monitored different parameters like treatment cycle of nodularizing elements, quality of base iron, cycle time, batch size, temperature, mechanisation and physical limitations for the good quality production of ductile iron who meets the industrial requirements basically in automotive industry. Since the discovery of ductile iron in the 1940's and its introduction to the industry in 1948, many materials & methods for treating magnesium with molten metal have been introduced, adopted or rejected by U S Foundrymen. Addition of spherodising element (magnesium) is the most important single step used for ductile iron production. Since magnesium posses a low vaporization temperature, its introduction to molten metal must be accomplished with care and consistency. Without predictable magnesium retention the entire ductile iron process fails. David matter adopted both open ladle& sandwich method as nodularizing methods for ductile iron production. Recovery of magnesium from the treated metal is the most important and consistent step in the process of producing ductile iron. A long list of variables influence recovery among them, base iron chemistry and temperature, nodularizing additive concentration and size, quantity of treatment and tapping rate and the treatment method. A variety of nodularizing methods are available for quality ductile iron production. No simple rules can be offered for the selection of any one process by an individual foundry [25].

3.4 A Brief Review of work done by Earlier Researchers

From the available literatures, it is quite evident that many attempts have been made to produce, to understand and to predict the behaviour of spheroidal graphite iron and its industrial applications which include the graphite morphology analysis and its evolution, the response of matrix structure to heat treatment, both structure-property correlation and effect of different processing variables on the mechanical properties of nodular iron in as-cast condition and its related applications. A brief review of some literatures in these areas is presented in this section.

M. Hafiz has investigated the mechanical properties of SG-iron with different matrix structure. Spheroidal graphite (SG) irons with a variety of matrix-structure have been produced by standard foundry practices. The investigation was carried out to study tensile properties, impact toughness, hardness and pearlite content. The use of different heat treatment processes resulted in percentage variation in pearlite content ranging from 0 to 95 percent. There is a remarkable consistency in the relationship between mechanical properties and pearlite content. Different heat treatment procedure produces different amount of pearlite. The yield and ultimate tensile strengths are increased with increasing pearlite content in the matrix structure. For matrix structure with 94.6% pearlite, the increase in these two properties are about 91% and 98%, respectively, compared with those of the ferritic matrix material. The impact toughness of SG-iron is influenced significantly by the matrix constituents. Energy of about 103 J/m^2 is required to fracture a ferritic matrix SG-iron. On the other hand, when the matrix structure approaches to a fully pearlitic matrix the fracture energy is decreased by an amount of 75.5%. The Brinell hardness value has been found to increase with increasing pearlite content in the matrix structure of the present material. It increases from about 128 for a fully ferritic matrix to about 258 as the matrix structure approaches a fully pearlitic one. The change in the hardness value has also been reflected in the mechanical properties presented in this investigation.

The results of the study show that the SG iron with ferritic matrix (18.9% of elongation) is more ductile and significant amount of deformation takes place prior to fracture. On the other hand, material with fully pearlitic matrix (SG iron with 50-60% pearlite) an unforeseen load may cause failure.

Pearlitic grades of SG iron are good for industrial applications requiring only high strengths and limited ductility and toughness and are generally not recommended for use in applications requiring impact resistance. The overall fracture path is controlled by initial nodule decohesion and growth of micro cracking at the graphite/matrix interface. It is thus the graphite-nodule distributions that dictate the least energy propagation path. The only operative mode for fracture of ferritic SG iron is the Dimple pattern of fracture. A fully ferritic matrix SG iron whose toughness is very low, a complex pattern of fracture is observed [26].

V.S.R. Murthy, Kishore & S.Seshan have investigated the formation of compacted graphite in cast irons. They adopted two methods for this process. Compacted graphite irons are a recent addition to the cast iron family. The graphite is in the worm like form and distributed in the matrix. For the production of this iron, a several methods has been adopted by the researcher and foundry men viz., extensive desulphurisation deliberate under treatment with magnesium and , cerium etc or combined treatment with spheroidising and anti-spheroidizing elements. It has been reported by many researchers that the mechanical properties of compacted graphite iron is intermediate between gray and ductile iron. The mechanisms of formation of spheroidal and compacted forms are still a matter of research, however it is believed that the addition of rare earth elements counteracts the effects of sulphur and oxygen, and encourages the growth of graphites in C-axis direction of hexagonal graphite crystals. Electron microprobe analysis was carried out in this investigation and the result reflects that the magnesium is concentrated at the centre of the nodule and other elements such as silicon and manganese present in the melt are concentrated at the graphite austenite boundry.In graphite nodule formation, rare earth sulphide or magnesium sulphide or a combination of the two is present at the nuclei of the nodule which results in the growth of graphite in spherical form [27].

Hila Gershi , Aharon Gedanken , Herbert Keppner & Hagai Cohen have correlated the results in this investigation by observing a reaction of pure carbon in microscopic shape of precursor structure under autogenic pressure at elevated temperatures for the thermal dissociation of several precursors including stearic acid, oleic acid, linoleic acid, methyl 3 butenoate, methyl butyrate, octadecane, octadecene, octane, octene and acrolein. They found that the dissociation of precursor under autogenic pressure at 700^0C results in the formation of pure carbon microstructure, spheroidal carbon in polarate form is obtained by heating octane. The thermal dissociation of some precursors yield prolate spheroidal shaped carbon while other precursors produce other morphologies. By this study they have concluded that the dissociation of materials with one double bond leads to a prolate spheroidal shaped pure carbon formation, whereas saturated precursors show a different morphology on a micrometer scale. A comparison between oleic acid and linoleic acid suggests that two double bonds do not give rise to the prolate spheroidal shape pure carbon [28].

Minoru Hatate, Toshio Shiota , Nobuyuki Abe, Masaharu Amano & Toshio Tanaka have investigated the bonding characteristic of spheroidal graphite iron and mild steel by using electron beam welding process. In this study, the electron beam welding was applied to both mild steel and spheroidal graphite iron and the weldability was investigated by considering the microstructure and mechanical properties. They applied two methods of welding process with high concentration of Ni (may prevent formation of cementite) addition in one method and in other method they adopted metal active gas welding process using a Fe-Ni wire. Application of electron beam on a spheroidal graphite iron specimen causes remelting on the surface and consequently rapid cooling takes place. As a result brittle fine-cementite structure is formed whose hardness is over Hv 700.Comparison of results establishes that the strength of SG iron is more than that of mild steel when both are subjected to electron beam welding process [29].

L.Collini, A. Pirondi, R. Bianchi, M. Cova & P.P.Milella have found that both the fatigue crack initiation and fatigue limit of the ductile cast iron are influenced by casting defects. In this investigation, they have experimentally studied the fatigue behaviour of ductile iron on a set of specimens extracted from heavy-duty tile press frames. Ductile cast iron is now a material of interest and is being used in different industrial sector especially in automotive industry and defence sector because of its relatively low cost & there is the possibility of controlling the matrix structure and the process of graphite spheroidisation.There are some particular, ferritic ductile irons having a huge diffusion because of their good strength & high ductility. The samples were machined as per the standard and made compatible with the instrument (Amsler FP 422 axial resonant testing machine) for testing purpose. The experiment was performed and the result was analysed to study the influence of casting defects. It was established that casting defects viz., porosities and shrinkage had a strong influence on the fatigue behaviour of ductile iron [30].

M.I.Imasogie & U.Wendt have characterised the shape of graphite particle in spheroidal graphite iron by using a computer based image analyzer. In order to correlate the structure-property-quality assessment, a procedure and specification for evaluating the degree of spheroidization of graphite in spheroidal graphite iron (SGI), using a computer-based image analyzing system has been developed .A computer based MACROS III analyzer and a CCD video camera were used in this experiment for alalysing purposes. Programming related to numerical indices was made and implemented using a Zeiss Jenaphot 2000 projection microscope and SEM. The modular procedure was used to evaluate the variation in the degree of spheroidization of graphite. Spheroidal graphite cast iron contains small graphite particles in the form of spheroids in the metallic matrix. It is well known that all of the mechanical and physical properties of spheroidal graphite iron depend on the shape of graphite nodules embedded in the metallic matrix such that initially its bulk physico-mechanical properties are determined primarily by the steel-like matrix. Any disorderness in the shape of nodules and its placement in the matrix may cause a drastic deviation from properties as per ASTM standard. By this investigation a correlation between the degree of spheroidization and 0.2% offset Y.S was established for ductile iron castings and also it has been observed that the properties of the spheroidal graphite cast irons depend largely on the graphite morphology [31].

Sanghoon Jung, Takashi Ishikawa & Hideo Nakae have investigated the critical conditions for the formation of graphite in nodular forms. The experiment was carried out in a He–3% H_2 atmosphere by using sessile drop method. It was observed that the interfacial energy between the Fe–C melt and basal plane of graphite (γGr/L) and the cooling rate on the formation of spheroidal graphite was influenced by the presence of sulphur in cast iron. It is observed from the result that the γGr/L decreased from 2.62 to 1.48 J/m^2 with an increase in the sulphur content. Simultaneously the corresponding surface energy of the graphite, (γGr/V) also varied from 1.17 to 0.65 J/m^2. It is observed that the graphite in spheroidal is formed when the γGr/L is greater than 2.5 J/m^2, which is the critical interfacial energy of the spheroidal graphite formation. Similarly the cooling rate also plays an important role for producing the spheroidal graphite in the Fe–C alloy. This signifies that the critical cooling rate is a function of the sulphur content in the Fe–C melt. It is also revealed that spheroidal graphite is not formed in the Fe–C melt with sulphur content of 86 mass ppm, even if cooling rate is 1000K/min. However this can be possible under the cooling rate of 100K/min if the sulphur content in Fe-C melt is 11 mass ppm. Similarly spheroidal graphite can be formed at 20 K/min for the 1 mass ppm samples [32].

M.A.Neri & C. Carrerio have investigated that the presence of copper content in the Fe-C melt of the nodular iron influences the morphology and mechanical properties of modified nodular iron. This experiment was carried out in two specific crankshafts. These crankshafts were under drilling operation and the drilling tool was failed in one of the crankshafts. A failure analysis was carried out in same crankshaft and it was observed that the same crankshaft had a fine pearlitic microstructure and greater hardness as compared with the other one. This may be due to higher content of carbon and copper in the matrix of the first crankshaft. In the Pearlitic ductile iron, graphite spheroids are uniformerly embedded in a matrix of pearlite. Pearlite is a fine lamellar aggregate of ferrite and cementite (Fe_3C). The presence of copper influences the mechanical properties viz., more hardness, moderate ductility and high strength. Although, pearlitic ductile iron is easy to machine & casting, it resist wear and impact toughness, reduces thermal conductivity, low magnetic permeability and high hysteresis loss. The presence of highest carbon and copper contents in the crankshaft, promotes the fine pearlite. The higher hardness of the fine pearlite results in poorer machinability in the crankshaft causing the failure of the drilling tool [33].

A.I.Al-Ghonamy, M. Ramadan, N. Fathy, K.M.hafez & A.A.El-Wakil have investigated the effect of graphite morphology on mechanical Properties of spheroidal graphite iron for Waterworks Fittings and Accessories. Materials with requisite properties serve as an enabling technology and contribute to the society in every aspect of requirement in case of machineries and social demands as per advanced technology. The civil and environmental profession can contribute to the improvement in the quality of life and standard of living by seeking solutions to infrastructure deterioration, hazard mitigation, structural safety, sustainability, environmental protection, and construction. In this study, ductile iron materials used for water works fittings & accessories were taken for investigation. Ductile iron is being used in waterworks fittings and accessories for a long time. But its mechanical properties are fully depending on nodularity of the graphite. For designing certain components, the material selection will be based on international standard ISO 2531 which does not suggest the minimum required value of nodularity of graphites & its influence on mechanical properties. The material especially ductile iron was analysed. The four types of ductile iron was produced by treatment with spheroidising (Mg) and anti-spheroidizing (Ti) elements. By this method Different degrees of graphite nodularities from low graphite nodularity of about 21% up to high graphite nodularity of 94% were produced. It is observed with increase in graphite nodularity, the mechanical properties viz., strength & ductility decrease & properties related to failure (tensile strength & impact toughness) are more influenced by the change of graphite nodularity. The minimum graphite nodularity for waterworks fittings & accessories may be considered to be 60% for all DN values [34].

Gulkan Toktas, Mustafa Tayanc & Alaaddin Toktas have investigated the influence of matrix structure on impact property of an alloyed spheroidal graphite iron. Ductile irons are very unique engineering materials because of its relatively low cost production, good castability, and good machinability. Based on these advance properties, spheroidal graphite irons are being used in different structural applications viz., Steering knuckles, hypoid rear axle gears, wind mill parts, crankshafts and disk-brake callipers for different applications. Ductile irons are also used in agricultural machineries. It is also observed that almost all members of ductile iron contain roughly graphite in nodular form in their matrix and it occupies volume around 13 to 15 percent in the matrix. Hence the influence of the matrix structure on mechanical and physical properties should not be avoided. An investigation was performed by taking a ductile iron sample (1.03wt% of Cu, 1.25 wt% of Ni & 0.18wt% of Mo) to examine the effect of the matrix structure on the impact properties of the nodular iron. All the samples were first homogenized at 925 °C for 7 hour in order to get a fully ferritic structure. Different heat treatment process were carried out to get different matrix structures viz.,pearlitic/ferritic, pearlitic, tempered martensitic, lower and upper ausferritic matrix structures. The impact strength (charpy) was calculated for all the homogenised samples in the temperature range between −80 °C and +100 °C. Other mechanical properties viz., the tensile strength, 0.2% offset yield Strength, elongation and the hardness of the matrix structures were investigated at room temperature. The graphite morphology, matrix constituents and the fracture surfaces of the impact specimens tested at room temperature were also analysed by Image analyzer and scanning electron microscope. It is observed that ductile iron possessing ferritic matrix shows best impact properties. spheroidal graphite iron with a lower ausferritic matrix had the best combination of tensile strength, ductility and impact strength of all structures [35].

Ali M. Rashidi & M. Moshrefi-Torbati have studied a correlation between the mechanical properties of ductile iron with dual matrix and effect of tempering conditions. Basically tempering refers to one of the important heat treatment processes, applied to quenched steels and cast irons. By applying this process, the brittleness of the material is reduced with remarkable improvement in toughness and ductility along with reduction of crack formation in the material. The material (ductile iron) was produced in an induction process as per standard foundry practices and tempering process was carried out. It is found that with the tempering temperature range of 450-500^{o}C, the material shows high impact strength with improvement in ductility. With increasing the tempering period up to 120 min, there is a decrease in tensile strength and yield strength. However impact strength persists for a period up to 90 min & ductility increases up to 120 min. For any combination of tempering temperature and time (tempering period up to 120 min), the tensile strength can satisfactorily be obtained from the master-curve's strength-tempering parameter [36].

C.A.Cooper, R.Elliott & R.J.Young have investigated the elastic property relationship for flake and nodular cast iron with the help of Raman Spectroscopy. The presence of magnesium, sulphur & phosphorus in the cast iron inhibits the structural & mechanical properties of the said material. It is known that in gray cast iron, carbon is present in the form of graphite & in white cast iron it is present as combined (Fe_3C) form. The graphites in spheroidal graphite iron are distributed throughout the matrix in the form of spheroids & in flake irons as interconnected graphite flakes. Now –a- days, Raman Spectroscopy is applied to different carbon base material for characterising the structure and mechanical properties. In this investigation, the researchers applied Raman spectroscopy upon deformed micromechanics of flake and nodular cast irons. The result shows that the Raman band peak positions of the graphite shift to a lower wave number during tensile deformation, and to a higher wave number in compression. Various theoretical models have been applied to characterize the elastic properties of cast iron. It has been found that Young's modulus is in close agreement with the models for disk-shaped inclusions for flake irons, and with models for spherical inclusions for the spheroidal graphite iron. If the graphite stress at 1% strain, the same models underestimate the stress reached in the graphite. This may be due to breakdown of the interface between the graphite particles and the iron matrix. It is also observed that Raman spectroscopy may follow the elastic recovery of the cast iron and can pinpoint the onset of permanent plastic deformation by comparing the peak positions of the Raman before and after unloading [37].

Hideo Nakae, Sanghoon Jung & Takayuki Kitazawa have investigated the eutectic solidification mode of spheroidal graphite cast iron & graphitisation. It is well known that both the shrinkage & chilling tendency of spheroidal graphite iron is more than that of flake graphite cast iron. This may be due to difference in their graphitization during eutectic solidification. The difference in the solidification mechanism has been studied in this investigation for both the cast irons. The eutectic solidification rate of the spheroidal graphite iron is controlled by the diffusion of carbon through the austenite shell and the final thickness is 1.4 times than the radius of the spheroidal graphite. In case of flake graphite cast iron, the rate of graphitisation is not only controlled by the diffusion of graphite in austenite shell but also in liquid. Therefore, with the reduction in radius, the number of nodule counts increases which may lead for producing good graphitization in the SG iron castings [38].

M. Shirani, G.Harkegard & N. Morin have predicted the fatigue life of the components made of spheroidal graphite cast irons. In case of cast materials, the crack growth may be initiated due to the presence of inclusions, variation in graphite morphology and metallurgical defects. These defects are considered as input parameters for the fatigue life assessment. The fatigue strength can be studied for the defects initiated by inclusions using fracture mechanism for cast materials. Defects initiate fatigue crack in most of the cast material. The fatigue life of components made from spheroidal graphite cast iron is determined by considering maximum defect size and its distribution in ferritic matrix. The fracture mechanism is applied to calculate the fatigue life by estimating maximum defect size through Gumbel distribution method. Fatigue crack growth simulations were performed to determine the lower bound of S-N curves for fatigue specimens [39].

L.C.Chang, I.C.Hsui, L.H.Chen & S.T.Lui have investigated the influence of graphite spheroids on the particles erosion of spheroidal graphite cast irons. Specimens with four different matrices viz., ferrite, upper banite, lower bainite & martensite were taken for investigation. For a two-phase alloy, the erosion behaviour is not clearly understood especially for materials which soft-phase like graphite cast iron. In this experiment, it is observed that graphite nodules with ferritic or upper banitic matrix don't exert any influence. However spheroidal graphite cast irons having martensitic matrix influence the erosion rate. On the other hand, if the nodule counts are increased in case of graphite cast irons with lower bainitic matrix, it increases the erosion rate for sand mould castings and decrease for metal mould castings. The normal angle erosion rate strongly depends on the matrix structure and generally increases in the order martensite, lower bainite, upper bainite & ferrite [40].

Makoto SOHMA found a relation between growth characteristics and graphite nodule size in his investigation. Two spheroidal graphite iron specimens were taken from the same molten metal with one contains coarse graphite grains and other contains fine grains to compile the growth theory of irreversible migration of graphite for this investigation. Both the samples were heated cyclically in still air and the relation between growth characteristics and the change of graphite phase of different size of graphite nodules was examined. From the evidence of redistribution of graphites followed by growth kinetics, the growth theory of irreversible migration of graphites became evident. Growth characteristics of spheroidal graphite iron are enhanced by nodule size. For bigger nodules, the growth rate is likely to be increased. It is understood from the growth theory of irreversible graphite migration; heat resistance of spheroidal graphite iron castings is in parallel line with the size of the spheroids [41].

C.G.An & H.Li etal., have found in their investigation that flake graphites are transformed into spheroids in liquid nickel. Graphite spheroids with diameter ranging from 300 to 1µm have been extracted by the acid erosion of the nickel & have been characterised using various techniques. Graphite spheroids having surface defects and atomic stacking are also observed. This is also in accordance with Raman spectrum. Now-a-days research works are being carried out to correlate kinetics of growth of graphite nodules and graphite morphology with high conductivity, corrosion resistance and lubricating ability etc. In this investigation, the flake graphite is subjected to molten nickel at high temperature (1550^{o}C) and subsequent process is followed. The phase identification is determined by x-ray diffractometer & the morphology is investigated by scanning electron microscopy. After successful experiment & analysis, it is found that flake graphite can transform in to spheroidal graphite in liquid nickel [42].

A.Scozzafava, l.Tomesani & A.Zucchelli have applied a fully automating image analysis operation to closely monitor the matrix constituents, nodule size, nodule counts and overall the matrix constituents. Different grades of spheroidal graphite irons are analysed in different environments and its influence on graphite morphology is studied. Mechanical properties of spheroidal graphite cast irons are influenced by processing variables. In general, all the mechanical properties depend on chemistry of the molten metal, the physical state of the liquid iron and the solidification process. To ascertain the possibility of fully automating the image processing on different grades of SG iron, a quantitative analysis of the micro constituents is needed [43].

M.Ashraf Sheikh & Javed Iqbal have investigated the change in graphite morphology, nodule count and nodularity by the addition of a single rare earth metal (It is like to be Lanthanum). A good quality of charge is made and the metal is produced in an induction furnace with variable in composition. Standard procedure is made for sample preparation as per standard foundry practices. The microstructure is analysed with the help of Image Analyser. From the analysis it is found that with increase in wt% of lanthanum, the nodule count in the ductile iron increases which indicates that rare earth plays an important role in improving the mechanical properties. The highest nodule count of 467 is obtained with the addition of 0.03 wt % of lanthanum in the melt but lanthanum has negligible effect on nodularity. As per foundry practices, it is known that an appropriate amount of rare earth is often used in the production of ductile iron castings to counteract the deleterious effects of subversive elements like titanium, bismuth and so on. However, addition of excess amount of rare earth elements is strictly forbidden as it promotes the formation of chunky graphite. The addition of rare earth elements has marked effects on the mechanical properties of spheroidal graphite iron castings. Morrogh and Wallance et.al have reported that small amount of addition of cerium, controls effect of the deleterious elements such as lead, arsenic, antimony, titanium, and tin [44].

Mahmoud Hafiz has correlated the tensile strength, elongation and hardness with the microstructure of a ductile iron which is subjected to uniform austempering procees before carrying out the experiment. He has taken two samples and both are austenised at 1183 K and quenched in two salt baths kept at 593 K and 723 K. After quenching, the former is steadily heated to 723 K and later is slowly cooled to 593 K. It is observed that the specimen who is quenched to 593K and then steadily heated to 723 K has high 0.2% offset yield strength, tensile strength, hardness. But ductility is much more less than the specimen which is austempered at 723K and slowly cooled to 593 K. The mechanical properties of spheroidal graphite cast iron can be greatly enhanced by austempermg heat treatment process because of graphite spheroids are uniformly embedded in the metallic matrix and the matrix constituents can be controlled by austempering process [45].

M.M.Haque has investigated the difference in fluidity, shrinkage, carbide formation, graphite morphology by taking two ductile iron specimes with different chemical composition. He made these samples with one consisting of Fe-C-2Si alloy and other consisting of Fe-C-Al alloy. With successful completion of experiment, he found that Fe-C-Si cast iron had more fluidity where as Fe-C-Al cast iron developed more shrinkage. For both the cast irons, the carbide formation in the microstructure decreases with increase in section thickness. The solidification characteristics of Fe-C-Al cast iron are more complicated than that of Fe-C-2Si cast iron. Because of improvement in matrix structure, the mechanical properties of Fe-C-2Si cast iron are enhanced as compared to Fe-C-2Al cast iron. Some Researchers have made attempts to replace silicon by aluminium by taking special inoculation technique and feeding arrangement as metallic aluminium and silicon have a similar effect on iron–carbon alloy system [46].

J.P Monchoux, C.Verdu et.al have investigated the partial dissolution of spheroidal graphites in ductile cast iron by performing two heat treatment processes. They observed that dissolution is taking place along crystalline defects of the spheroid regularly spaced out around it. A growing matrix disturbs these locations, spheroidizes and then detaches itself from the matrix by producing an enclosed matrix particle in the graphite. Estimation is prepared comparing with the existing model of globulization kinetics. The presence of silicon in the matrix plays a role on the dissolution rate and on the resulting graphite–matrix interface. Formations of matrix intrusions and growth into spheroids have been found through SEM & TEM analysis. The particles detach themselves from the matrix and are incorporated in to the graphite spheroids [47].

G.Vertesy, T.Uchimoto, I. Tomas, & T.Takagi have developed a novel non-destructive method by magnetic adaptive testing. A correlation of magnetic descriptors with Brinell hardness and conductivity is made for spheroidal graphite iron. Four series of stair-case samples are taken for this investigation with different cooling rate during casting resulting in different microstructures of all the specimens. Sensitive descriptors are found by magnetising the samples with the attached yoke. This happens only due to measurements of series of magnetic minor hysteresis loop without magnetic saturation of the specimens. A good correlation is obtained by comparing non-destructive tests with Brinell hardness and conductivity. Since, magnetisation process is related to microstructure, magnetic measurements are frequently used for characterising the ferromagnetic materials [48].

D.D.Double & A.Hellawell have explained the nucleation and growth of the graphite in the molten metal during precipitation when the melt is subjected to solidification. The precipitation of graphites in the molten metal is considered to occur in freely the melt. All graphites precipitating in the molten metal are originating from a basic hexagonal ring like structure which consequently grows to spheroids. These alternatives may be due to kinetics in the molecular attachment. In a clean melt, spheroidal graphite is a preferred morphology where as flake graphite is an impurity modified form and its fullerenes growth is unpredictable. Spheroidal growth is possible in clean melt because the melt is free from oxygen, sulphur and less possibility of availability of phosphorus. Hence the growth starts with minimum activation energy [49].

Pierre Diericks, Catherine Verdu et.al have studied the possible parameters responsible for the damage of heat treated and as-cast spheroidal graphite iron casings. They found that mainly physico-chemical mechanisms play a vital role for this phenomenon. To understand the microstructure and damaged mechanism, they have taken two damaged samples. In first sample, the damage initiates at the matrix-graphite interface and in second sample, the damage is inside the graphite. Microstructural characterisation and mechanical behaviour for both the samples are studied and the influences of different microstructural parameters are estimated. Most of the mechanical applications are made with ferritic spheroidal graphite cast irons. The ferritic matrix can be obtained during as-cast condition or subjecting to certain heat treatment process which transforms pearlite to ferrite & graphite. The final microstructure appears to be same but there is variation in mechanical properties [50].

Zhiyong He, Jinxiang Zhao & Zhong Xu have found the much more improvement of surface hardness of the spheroidal graphite iron when it is subjected to plasma surface alloying. Plasma W-Mo and Ni-Cr are used for this investigation. The spheroidal graphite iron which is plasma surface alloyed with W-Mo exhibits more surface hardness (surface hardness increases from 200 to 1500Hv) than surface alloyed with Ni-Cr which increase to 600 HV. It is observed that plasma surface alloying enhances the corrosion resistance of the cast iron. The alloy content and hardness of the alloyed layer on the cast iron manifest a gradually decreasing tendency from surface to the inside of the substrate. Sphrroidal graphite cast iron is widely used as structural material in manufacturing as well as in automotive industry. It has a certain level of wear resistance and ability of vibration. Hence surface modification is required to operate in all possible environments. As spheroidal graphite cast iron is a low cost production material and widely available, it will be used as new usage by applying this technique [51].

Sugwon Kim, S.L.Cockcroft & A.M.Omran have optimised the process parameters in their investigation. They have studied the different parameters viz., chemical composition, holding time, temperature and thickness of the casting during production of compacted graphite cast iron. They observed that nodularity increased with increasing percentage in residual Mg where as with increasing wt% of Cu, there is increase in pearlite content in the compacted graphite iron. The mechanical properties also enhance with increasing the wt% of residual Mg under controlled parameters during compacted graphite iron formation. It is known that compacted graphite iron possesses distinctive mechanical and physical properties which are intermediate between those of grey cast iron and ductile cast iron. Compacted graphite iron gives more tensile strength (at least 70% higher), more elastic modulus (35% higher) and approximately double the fatigue strength of a conventional grey cast iron. The most important applications of compacted graphite iron are in the manufacturing of automotive engines, machine parts and rolls for various applications [52].

J.M.Guilemany & N.Llorca-isern have investigated the relationship between microstructure and properties of unalloyed compacted graphite cast irons. For this study, two austempering temperatures viz., 400^{o}C & 300^{o}C were chosen. The result of influence of ferritizing treatment prior to normalising & austempering was determined. It is found that there is no additional advantage. The relation between microstructure with properties was analyzed. The result showed that ferritization prior to bainitic treatment would decrease the hardness, tensile strength & dynamic elastic modulus. If the ferritie-banaite content is more in the microstructure, it leads to increase the percentage of ductile fracture in the fracture surface. More carbide level enhances the more brittle fracture mode [53].

J.Lacaze has made a useful tool to predict the development of microstructure and micro segregation during solidification of spheroidal graphite iron. For preparing this model, he took mainly two input data viz., melt chemistry and inoculation practices. He examined the main effect of redistribution of substitutional species on the solidification behaviour of spheroidal graphite cast iron and the final microsegregation in as-cast condition. The possibility of metastable eutectic to nucleate and grow is also considered. Microsegregation affects the mechanical properties of the cast iron. Hence it is a matter to investigate it during solidification of the melt. This investigation helps to account the actual composition of the cast irons which may be hypoeutectic, eutectic or hypereutectic, with respect to the relevant phase diagram. It is observed that neither the solidification nor the graphite nucleation kinetics is significantly affected by the build up of microsegregation during solidification of cast irons, but during eutectic reaction, there may be the chances of formation of large chemical heterogeneities which are negative for gray solidification and positive during white solidification. If solidification proceeds through stable system, then the final segregation of the silicon is not highly sensitive to cooling conditions, inoculation methods and carbon content in the melt. However the micro segregation pattern changes with some white eutectic deposits if the cooling rate is increased or there is a decrease in inoculation efficiency [54].

X.Zhao, T.F.Jing, Y.W.Gao, J.F.Zhou & W.Wang have developed a severe deformation process (SPD) for cast iron named cyclic covered compression (CCC). Any material that is processed by SPD process has the tendency to attract the growing interest of materials specialist in the study of material science because SPD material possesses unique physical & mechanical properties. Some SPD process viz., equal channel angular processing, high pressure torsion, multi-axial compression and accumulative roll-bonding have been developed to meet these properties. However few literatures are available concerning SPD process of cast iron. The main reason for not availing more literatures may be the difficulty in obtaining specimens without crack. In the present investigation, the specimens are embedded in a steel cylinder and they are hot compressed. Then the treated specimens are cut, machined out of surface layers, stacked and embedded into steel cylinder and again subjected to hot compression. In the CCC process it is observed that spheroidal graphite iron is 92% compressed in height reduction. The shape ratio of deformed graphite (β) increases till the extent of reduction increases up to 80%. Therefore β does not change with reduction [55].

Jaw-Min Chou & Min-Hsiung Hon have studied the isothermal austenization transformation in an unalloyed ferritic ductile iron casting over the temperature ranges from

880°C to 953°C. There are many thermal processes which have been developed to modify the graphite morphology in order to enhance the mechanical properties. Some process like austenisation, austempering or quenching has received a great response because of enhancing physical properties of spheroidal graphite iron castings. In this process, a variety of microstructure with different combinations like ferrite-bainite-retained austenite,ferrite-martensite-retained austenite and ferrite-bainite-martensite is obtained resulting in different mechanical properties. The kinetics of austenization plays an important role in controlling the final volume fraction of the second phase. However now the decomposition of austenite is a matter of concern and more attention to be given for understanding its kinetics. During austenite transformation, the most preferential place for nucleation of austenite is at cell boundary and graphite – ferrite interface and its growth is accomplished by an up-hill boundary diffusion of carbon to cell boundaries. The activation energy for austenization process is 267.2kJmol^{-1} and half of this energy is required for interface-controlled process. It is evident that austenization is a carbon diffusion controlled process. This conclusion can be drawn from study of microstructural observations, transformation kinetics and activation energy [56].

R. Dommarco, I. Galarreta, H. Ortız, P. David & G. Maglieri have studied the use of wheel loader bucket tips made of ductile iron and austempered ductile iron. The buckets are processed at intermediate and low austempering temperatures. From the field tests carried out for bucket tips made up of austempered ductile iron (ADI), it is observed that ADI is more advanced than low alloy steel commonly used for this application. Both spheroidal graphite iron and ADI have an excellent resistance to severe abrasive wear without any failure event due to low fracture toughness. From the X-Ray diffraction analysis, it is found that a small fraction of the austenite phase transformed to martensite under strain induced in service.

Hence this is not the main effect responsible for the observed high resistance. A conclusion line may be drawn from the experiment that high ausferrite ductility and its related energy consumption capability are mainly responsible for the high E-values observed. Both the pearlitic and martempered spheroidal graphite iron (SG iron) posses high abrasion resistance and can be used as alternative materials for wear applications [57].

O.P.Ostash, E.M.Kostyk, I.M.Andeiko and M.M.Dronyuk have observed the effect of microstructure on the low temperature cyclic crack growth resistance of high strength cast irons. The influenced of temperature on the cyclic crack growth of high strength nodular cast iron is studied in the temperature ranges from 77-293^{o}K for different types of matrices. It is observed that when ferritic high strength nodular cast iron is subjected to high temperature annealing followed by hardening & tempering & characterized by satisfactory low temperature fatigue crack growth resistance. It is found that the characteristics of cyclic crack growth resistance of the investigated types of high strength nodular cast irons are not less than the corresponding characteristics of cold resistance structural steels frequently used in mechanical engineering [58].

P.Larranaga, I.Asenjo, J.Sertucha, R.Suarez, I.Ferrer and J.Lacaze have investigated the effect of antimony and cerium on the formation of chunky graphite during solidification of heavy section castings of near eutectic spheroidal graphite (SG) irons. For this study, four melts were made in a single cast house and poured in a mould. The casting size is 30cm in thickness with variable in cerium percentage. Post inoculations were carried during casting and cooling graph and were recorded in the centre of the casting. It is observed that solidification proceeds in three steps viz., primary deposition of graphite followed by an initial and then a bulk eutectic reaction. It is clear that the formation of chunky graphites takes place during the bulk eutectic reaction and antimony hinders the amount of chunky graphite formation. It is evident that the solidification of near eutectic heavy section castings starts with the precipitation of primary graphite nodules followed by austenite growth. After this initial eutectic reaction proceeds some time, the chunky graphite starts nucleating and there growth is increased by the bulk eutectic reaction [59].

R.Salazar F, M.Herrera-Trejo,M.Castro, J.Mendez N, J.Torres T & M.Mendez have studied the effect of nodule count and cooling rate on as-cast matrix of a Cu-Mo spheroidal graphite iron. It is known that the transformation from austenite to ferrite & graphite or to pearlite in a spheroidal graphite iron castings depends upon a number of factors. Among them, nodule count and cooling rate has been investigated in this study. It is observed that the pearlite fraction is decreased as the nodule count is increased for a given cooling rate. However with increase in cooling rate, the pearlite fraction increases. Both the cooling rate and pearlite fraction are more sensitive at low nodule count. The Cu-Mo graphite cast irons were produced in a medium frequency induction furnace. This was followed by the addition of different amounts post-inoculants in order to obtain different nodule counts. It is found that both nodule count & cooling rate affects the relative amount of pearlite and ferrite in the matrix by analysing the matrix and studying the effect of inoculation [60].

S.Jung, T.Ishikawa, S.Sekizuka & H.Nakae have investigated the effect of sulphur on interfacial energy between Fe-C melt and graphite. The sessile drop method was used in this study. The method is generally used to measure the equilibrium contact angle of molten Fe-C-Si alloys on graphite basal planes. The interfacial energy ($\gamma_{s/l}$) was measured between the basal plane of the graphite and Fe-C melts at 1573K in a purified He-3%H_2 environment. The surface tension ($\gamma_{s/v}$) of the melt was also determined. With the help of optical microscope, both the contact angles θ and ϕ were measured where θ is the contact angle between the liquid metal and graphite substrate and ϕ is the hidden angle observed at cross section of the sample. From the experiment, it is observed that both the interfacial energy and surface tension decreases when sulphur content is more than 10mass ppm. The graphite morphology changes from spheroids to flakes due to decrease in interfacial energy value as there is increase in sulphur content in the melt [61].

F.T.Shiao, T.S.Lui, L.H.Chen & S.F.Chen have investigated the eutectic cell wall morphology and related tensile embrittlement. For this study, four ferritic spheroidal graphite irons with different carbon and silicon percentage (3.4C-3.9Si, 3.5C-2.7Si, 3.5C-2.0Si & 2.0C-2.1Si in wt %) are taken. It is observed that the average cell wall size and the amount of cell wall inclusions decrease with decreasing silicon concentration. The specimen with composition 3.5 % C, 2% Si has many inclusions dispersed in the ferritic matrix. On the other hand, the specimen with 2% C, 2.1% Si posses larger cell wall size and larger degree of inclusion clustering in the cell walls. Tensile strength embrittlement may occur in the intermediate low temperature range or at the intermediate high temperature range around 400^0C. The preferable location for the development of brittle cracks is at the inclusion clusters in the eutectic cell wall. The spheroidal graphite iron possessing larger inclusion clusters enhances the tensile embrittlement [62].

A.I.Traino, V.S.Tusupov and A.A.Kugushin have studied the graphite morphology and properties of a deformed heat treated high strength cast iron with globular graphite. It is well known that the high strength cast iron with globular graphite (HSCGG) is characterized by a combination of high mechanical, physical and anticorrosion properties. This material is now being used in welding because of its relative low cost of production and suitability for structural applications. For this investigation, the material was prepared in an open induction furnace as per standard foundry practices and the liquid melt was cast into moulds. After the material got hardened, it was subjected to graphitization annealing and different forms of plastic deformation viz., extrusion, rotation forging, length wise and helical rolling and drawing. The microstructure was studied with the help of optical microscope and the cross section of the specimen was analysed by X-ray method. The mechanical property was determined by an INSTRON tensile testing machine. It was observed from the experiment that graphite inclusions irreversibly lose their globular shape and extending along the direction of metal flow in the deformation source. The microstructure and the morphology of the matrix were affected by the heat treatment but the shapes of graphite in inclusion remain unchanged. This determines the level and isotropic nature of the mechanical properties of HSCGG which imposes certain constraints on the production process [63].

A.V.Lisovsky and B.A.Romantsev have investigated the enhancement of structure and properties of a cast iron during hot metal forming. Basically the forming method is applied to high strength spheroidal graphite cast iron in hot condition. The main problem arising in the industry is the improvement in quality and operating properties of components with a reduction in their production cost. The main industrial applications of cast irons are sleeves, compressors, the fingers of caterpillar machine tracks, gears, cam and crank shaft, gear wheels and other components. Traditionally these products are manufactured by castings. The result obtained from the experiment that the structure is typically extension of spheroidal graphite inclusions along the direction of metal flow and it enhances the mechanical and operating properties. The properties as desired can be considerably increased subject to there is a strong control on shape of the graphite inclusions and their distribution within the volume of a worked object [64].

C.A.Copper, R.Elliott and R.J.Young have investigated the graphite structure in flake and spheroidal cast iron using Raman Spectroscopy. This is an excellent technique for characterization of graphite in flake as well as in spheroidal cast irons. The Raman spectrum of graphite is highly sensitive to both structural ordering and residual stress and that can be observed from the Raman bands. A comparison has been made between the relative intensities with the widths of the G' of the Raman Bands for both flake and spheroidal graphite cast irons. The result corresponds to the degree of graphitization across the graphite. The two Raman bands viz., G^1_1 and G^1_2 (change in intensity and width with the distance across a graphite spheroid) are taken in to account for this study. From the analysis of the two bands, it is found that there is nothing discernible pattern which signifies the systematic change of graphite ordering along a graphite flake. Positions for both the bands remain relatively constant for both the specimens showing there is no residual stress in graphite for both the cases [65].

Richard Waudby, Peter Andersson & Kenneth Holmberg have investigated the scratch tester with a newly developed steel wire sample geometry replacing the conventional diamond tip resulting in effect of increasing load, loading rate and lubrication. In the investigation, a sliding couple consists of SG iron and steel wire was considered. The aim was to find out the relevant wear and friction information about the commonly used material. The result of the influence of loading rate and the lubrication of the steel wire slider was also compared with the results found by using diamond tips. Some characteristic failures of the nodular cast iron were recorded in optical microscope. These failures helped to determine the critical scratching normal loads. The scratch failures obtained in tests with diamond tips did not occur in tests with the pearlitic steel wire slider. So, the tip plays an important role for establishing the load dependency of surface failures of cast irons. The result obtained from the lubrication tests showed that at the start of the scratch, higher coefficient of friction was recorded due to surface roughness effects. To have a good control on friction, correct level of lubrication should be applied [66].

S.Vijayarangan, N.Rajamanickam & V.Sivananth have developed a metal matrix composite (MMCs) that will replace SG iron which is used in producing steering knuckle. SG iron is used in automobile industry for producing different components. But the current automobile industry really needs advance material which gives high strength to weight ratio. Steering knuckle is an important component in automobile suspension system and it is made up of with SG iron. Steering knuckle is always subjected to time varying loads during its service life, leading to fatigue failure. Since the component design is an important aspect, the present researchers introduced MMCs which would replace SG iron due to its high strength to weight ratio and would meet the requirements in materials design of an automobile industry. An aluminium alloy reinforced with Titanium carbide particulate (Al-10 wt% TiC) was used as a material of investigation. The performance result (on real time load case) obtained from the steering knuckle was compared with the aluminium alloy and SG iron. The life of the MMCs knuckle was evaluated for maximum load case. The result obtained from the numerical analysis and experimental results shows that the performance of MMCs knuckle is much better than SG iron knuckle with a weight saving of 55% when compared with conventional SG iron used for manufacturing steering knuckle [67].

Laurence Fouilland & Mohamed EI Mansori have investigated the ductile-brittle transition (DBT) in hot cutting of SG irons. The experiment for DBT of the primary shear zone was performed during cutting of SG iron in the austenization temperature range (around 1000^0C) by using a cutting test bench with maintaining cutting speed range 0.8-1.6ms^{-1}. The surface characterization was studied by optical microscopy and SEM techniques. The results showed that the deep fractured regions may be governed by the BCR (brittle cracking regime) or the crack-free surface may be due to ductile shear regime (DSR) with large plastic deformations. The deep cracks cut surface is related to BCR and is activated by cutting parameters viz., negative rake angle and high cutting speed which promotes strain hardening rather than strain softening. The metallographic analysis of the oil quenched SG iron sample shows that DBT is associated with the recrystallization initiated in austenite SG phase [68].

Rohollah Ghasemi & Lennart Elmquist have investigated the graphite extrusion phenomenon during microindenting and microscratching of cast iron. On the study of graphite morphology and the lamellar graphite contribution to tribofilm formation under abrasive conditions, it is observed that the matrix deformation occurs during a sliding wear condition and have a significant influence on its lubricating performance. The induced plastic deformation which is developed adjacent to the graphite, compressed the lamellar and extrusion of graphite taking place from its natural position. It is also obtained from both the indentation and scratch experiment, the graphite begins to fracture and extract from the centre of the graphite lamellar irrespective of the size of them. A mechanism is introduced to explain the self-lubricating and extrusion behaviour of lamellar graphite when subjected to indentation or scratch tests [69].

N.K.Vedel-Smith, J.Rasmussen & N.S.Tiedje have studied the thermal distortion of disc-shaped ductile iron castings in vertically parted moulds. A disc-shaped casting with inner boss and an outer rim, separated by a thin walled section was taken for this experiment. The main focus on this investigation was on two parameters viz., feeding modulus and alloy composition. When the deformation measurement was carried out on the specimen, it was observed that the degree of deformation was influenced by both the alloy composition and the feeder. The deformation in pearlitic alloy was influenced by changing the feeder modulus where as the deformation in fully ferritic alloy was less affected by change in thermal gradient. The deformation which took place in disc-shaped ductile iron castings depend on Silicon content of the material, moduli of the central feeder, modulus of the top feeder, porosity tendency indicated by micro-surface shrinkage at the boss and pattern adaption for production optimization [70].

Mingfang Zhu, Lei Zhang, Honglei Zhao and Doru M. Stefanescu have proposed a two dimensional multiphase cellular automation model for simulating microstructural evolution during divorced eutectic solidification of spheroidal graphite iron. SG iron is characterized by the presence of quasi-spherical graphite nodules distributed in the metallic matrix. The mechanical properties of the SG iron depend mainly on graphite shape, size and distribution. The presence of spheroidal graphite reduces the stress concentration and provides higher strength and toughness as compared to flake graphites. In this investigation, the model was used to calculate the driving force for the growth of both graphite and austenite phases. The density difference between the iron and graphite affects the growth kinetics of the graphite. The simulated microstructure, cooling curves and cooling rates were compared with the experimental data obtained. The simulation revealed that interactive and competitive growth between austenite dendrite and graphite nodules, and the graphite growth controlled by carbon diffusion through the solid austenite shell [71].

3.5 Ductile iron & Factors affecting its properties

Ductile iron is a special kind of material which exhibits a good combination of strength with ductility ensuring its huge application in heavy engineering industries. This is due to very typical microstructure owing to its melt chemistry, different types of heat treatment procedures, good quality grade raw materials and processing variables. Since its infancy, spheroidal graphite has been produced with the Fe-C-Si alloy system. A recent study by the National Centre for Manufacturing Sciences (NCMS) has found that by replacing fabricated structures by DI in certain machine tool applications. Many result in cost savings of 39-50% retaining better quality and more fatigue life in the materials during its service life.

Commenting on the NCMS study, Mr. Gary Lunger, president of Erie Press Inc. Stated, “We make huge presses and we have relatively clear specifications for what goes into each press. We have been able to use Ductile Iron as a substitute material primarily for cylinders and other parts at a significant cost saving over cast or fabricated steel” [75].

Some lists of important constituents which are responsible for its typical mechanical properties are discussed in this section.

3.5.1 Important Microstructural Components of DI

Basically DI may be referred to as natural composites whose properties are mainly depend on the microstructures and graphite morphology, the stable and metastable phases formed during solidification or subsequent heat treatment. The major constituents of the matrix are the chemical and morphological forms taken by the carbon and its distribution in the metallic matrix [76]. The following important microstructural components are found in DI.

3.5.11 Graphite

Graphite is referred to as stable form of pure carbon in DI. The main properties of graphite are low density, low hardness, high thermal conductivity and lubricity. The shape of graphite plays a significant role in determining the mechanical properties of DI. Ductile iron is characterised by having all its graphite in microscopic spheroids and it occupies 10-15% of the material volume, its compact spherical shape minimizes the effect on mechanical properties. The graphite are found not in perfect spheroidal form and somewhat irregular shape in commercially produced ductile iron, but it is still chunky as Type II in ASTM Standard A247; the properties of the DI will be similar to cast iron. The nucleation and growth of the graphite in to spheroids is established when the metal solidifies, and it cannot be changed in any way except by re-melting the metal. The difference between the various grades of ductile iron is in the microstructure, its constituents and graphite morphology. This microstructure varies with the chemistry of the melts and the cooling rate of the casting. It can be slowly cooled in the sand mould for a minimum hardness (as-cast) or, if the casting has sufficiently uniform sections, it can be freed of moulding sand while still at a temperature above the critical and can be normalized. The specific gravity of graphite that occurs in the ductile iron is 2.25 at room temperature [77].

3.5.12 Carbide

Carbide is an interstitial intermediate compound having fixed carbon content. It is a compound with high hardness, brittleness, low tensile strength and high compressive strength. It is a compound of carbon and either iron or any carbide forming elements viz., chromium, vanadium or molybdenum. It is slightly ferromagnetic up to 210^{o}C and paramagnetic above it. Under normal condition, carbon has a tendency to combine with iron to form carbide. However, under very slow rate of cooling, during solidification, carbon atoms get sufficient time to separate out in pure form as graphite. The melting point of carbide is around 1227^{o}C. Massive carbide increases the wear resistance of the DI and promotes brittleness which is very difficult for machining. Dispersed carbides in the matrix of the DI enhance the strength and wear resistance of the materials. The specific gravity of carbide that occurs in the ductile iron is 7.66 at room temperature [78].

3.5.13 Ferrite

Ferrite is an interstitial solid solution of carbon in alpha iron and is thus BCC in structure. It derives its name from Latin word ‘ferrum’ which means iron. It is the purest iron phase in a cast iron. The maximum solubility of carbon in ferrite is 0.02%. Ferrite is soft and ductile. It produces lower strength and hardness, but also high ductility and toughness in commercial DI. In austempered ductile iron (ADI), extremely fine grained acicular ferrite provides an exceptional combination of high strength with good ductility and toughness. The strength properties of ferritic ductile iron are generally increased by the elements, which go in to the solution. Ferrite is ferromagnetic in nature at low temperature and losses its magnetic properties with rise in temperature. The density of ferrite that occurs in the ductile iron is 7.86 grams/c.c. at room temperature [78-79].

3.5.14 Pearlite

Pearlite, produced by a eutectoid reaction and consists of a mixture of alternate parallel plates of ferrite and cementite. The structure composed of ferrite (87.5%) and cementite (12.5%). It only forms at specialized conditions which must be controlled to create this alloy phase rather than another one. It nucleates at the austenite grain boundaries. The nucleation rate of pearlite increases with decreasing austenite grain size. Brinell hardness of as-cast ductile iron increases markedly when the cooling rate through the austenite/ferrite transformation range is increased. This effect is related to the amount of pearlite formed during the transformation and to pearlite hardness. Higher cooling rates result in greater pearlite contents and hardness. The homogeneous fine pearlite can be obtained by air cooling the casting from the temperature range of $870^{o}C$-$940^{o}C$ subject to the melt chemistry (The melt should contain high Si and moderate Mn about 0.3-0.5 wt %). Air cooling also produces less proeutectoid ferrite in the matrix and eventually fine pearlite which shows there will be increase in hardness. The microstructure obtained in this process depends on the melt chemistry of the casting and the cooling rate. The cooling rate depends upon the mass as well as thickness of the casting, but the graphite morphology may be influenced by the atmospheric temperature and movement of surrounding air during cooling. Pearlite, as a common constituent of DI, provides a combination of higher strength and a corresponding reduction in ductility which meets the requirement of several engineering applications and thick section casting for wind mill components. The density of pearlite that occurs in the ductile iron is 7.78 grams/c.c. at room temperature [75, 79].

3.5.15 Martensite

Martensite is defined as a supersaturated interstitial solid solution of carbon in alpha iron. The diffusion rate of carbon decreases with lowering of temperature and at about $200^{o}C$, the diffusion rate is almost negligible. Austenite, when subjected to under cool below $200^{o}C$, transforms to a product called martensite. Carbon atoms are present at the interstices. It has a body centred tetragonal structure. The morphologies of martensites are lath martensite and plate martensite. The hardness of martensite is a function of carbon content. In the untempered condition, it is very hard and brittle. Martensite is normally subjected to tempering treatment to reduce its carbon content by the precipitation of carbides to provide a controlled combination of high strength, wear resistance and ductility. Martensite with hardness below 55Rc has some amount of ductility, but hardness above 60Rc, it is generally brittle. The density of martensite that occurs in the ductile iron is 7.63 grams/c.c. at room temperature [80].

3.5.16 Austenite

It is an interstitial solid solution of carbon in gamma iron and has FCC structure. It derives its name from ‘Sir Austin’ the maximum solubility of carbon in austenite is 2.11% at $1147^{o}C$ and decreases to 0.77% at carbon at $727^{o}C$. Austenite is soft, ductile, tough, malleable and non-magnetic. In austempered irons; austenite is produced by a combination of rapid cooling which suppresses the formation of pearlite and the super saturation of carbon (the austenite-to-martensite transformation starts far below the room temperature). In austenitic irons, the austenite matrix provides ductility and toughness at all temperatures, corrosion resistance and good high temperature properties, especially under thermal cycling conditions. In austempered ductile iron stabilized austenite, in volume fractions up to 40% in lower strength grades, improves toughness and ductility and response to surface treatments such as fillet rolling. The density of austenite that occurs in the ductile iron is 7.84 grams/c.c. at room temperature [75, 78].

3.5.17 Bainite

The term bainite refers to a mixture of ferrite and iron carbide which is produced by alloying or heat treatment. This ferritie-carbide mixture has a basic difference with respect to pearlite. Bainite, as the product of austenite decomposition was first reported in 1930 by Davenport and Bain and has been so designated in honour of E.C.Bain. The morphology of bainite is distinctly different from that of fine lamellar pearlite. The bainite is classified in to upeer bainite and lower bainite. The crystal size in bainite is submicroscopic [80].

3.5.2 Family of Ductile iron

The rapid growth of the ductile iron industry and the high annual utilization of ductile iron castings are testimonials to the outstanding mechanical properties, quality and economics of ductile iron castings. The automobile and agricultural implement industries are major users of ductile iron castings. The properties of ductile iron are considered basically in terms of matrix phases which govern the relative range of properties. With a high percentage of graphite nodules present in the structure, mechanical properties are determined by the ductile iron matrix. The importance of matrix in controlling mechanical properties is emphasized by the use of matrix names to designate the following types of Ductile Iron.

3.5.21 Ferritic Ductile Iron

Spheroidal graphites in a ferritic matrix provide an iron with good ductility and impact resistance and with a tensile and yield strength equivalent to low carbon steel. Ferritic ductile iron can be produced as-cast but may be given an annealing heat treatment to assure maximum ductility and low temperature toughness. The structure of ferritic ductile iron consists of pearlitic and ferritic, with the ferritic generally surrounding the graphite nodules in "bulls eye" arrangement. The percent of ferrite in the ferritic ductile iron can be expected to range from 60-85%. This depends upon the melt chemistry, section thickness and cooling rate [75].

3.5.22 Pearlitic Ductile Iron

Spheroidal graphites in a matrix of pearlite result in an iron with high strength, good wear resistance, and moderate ductility and improved impact resistant. Machinability is also superior to steels of comparable physical properties. As per our standard foundry practices, ductile irons castings are cooled in the mould to below the transformation temperature in order to avoid air hardening. The Brinell hardness of the pearlitic ductile iron normally ranges from 197-255 BHN. If a ductile iron shows hardness of 197 BHN, then the pearlitic percent in the matrix cab be expect from 40-50%. Brinell hardness is a measure of the percent of pearlite in the metallic matrix of the ductile iron [81].

3.5.23 Ferrito-Pearlitic Ductile Iron

Ductile iron is not a single material but it's a group of materials offering better properties which are obtained by controlling the microstructure either in as-cast condition or by certain heat treatment process. These are the most common grade of ductile iron in the DI family and it has wide range of applications in various components of different industrial applications and also in wind energy and are normally produced in the as-cast condition. The graphites in spheroidal forms are distributed in a matrix containing both ferrite and pearlite. The Properties of this grade DI iron are intermediate between ferritic and pearlitic grades, with good machinability and low production costs. Ferrito-pearlitic ductile irons are characterized by a very high nodularity of graphite spheroids embedded in the metallic matrix [84].

The above three types of DI are most commonly used in as-cast condition for different applications. As per industrial requirements and for some critical component manufacturing, the DI can be alloyed or heat treated to provide the following grades of DI for certain applications.

3.5.24 Martensitic Ductile Iron

Quenched and tempered ductile iron responds satisfactorily to induction hardening even when it has been tempered sufficiently to deplete the matrix almost entirely of combined carbon. The reason is that during the process of tempering a martensitic structure is formed. Secondary graphite nodules form within the martensitic areas and as tempering continues, the remaining martensitic carbon migrates to the nearest graphite particle. The tempering of a quenched –martensitic –ductile iron is a function of both time and temperature. Using alloy additions will sometimes stabilize the pearlite sufficiently and a ‘quench-temper’ heat treatment produces this type of ductile iron. The resultant tempered martensite matrix develops very high strength and wear resistance but with lower levels of ductility [75, 81].

3.5.25 Austenitic Ductile Iron

Austenitic ductile iron is produced by controlling the carbon and silicon at lower levels and adding various alloys to produce a suitable austenitic structure at ambient temperature. Basically nickel is used as alloying element for producing austenitic ductile iron as it stabilizes austenite during solidification. The high nickel content in austenitic ductile iron in addition with chromium in certain grades provides superior resistance to heat, corrosion and wear. This DI also offers good strength, ductility, controlled thermal expansion, good castability, good machinability and dimensional stability at elevated temperature [82].

3.5.26 Austempered Ductile Iron (ADI)

Austempered Ductile Iron is a ferrous cast material heat treated by the Austempering Process resulting a new material that is strong and tough with high strength-to-weight ratio. Considering the sustainability, ADI is a material/process combination with much to offer in sustainable engineering designs. Metal casting is the lowest energy path from earthen raw materials to finished product. The metal casting process produces less waste, has fewer process steps and consumes less energy than hot or cold forming, extruding or welding. The mechanical properties of ADI depend on microstructure shaped in a two-stage heat treatment process, which consists of austenitising and austempering.The matrix is mainly bainitic but depends on the time and temperature. The two main parameters of this process, it may contain a considerable amount of other constituents. Nearly twice as strong as pearlitic ductile iron, ADI still retains high elongation and toughness. This combination provides a material with superior wear resistance and fatigue strength [83].

3.5.3 Factors Affecting Properties of Ductile Iron

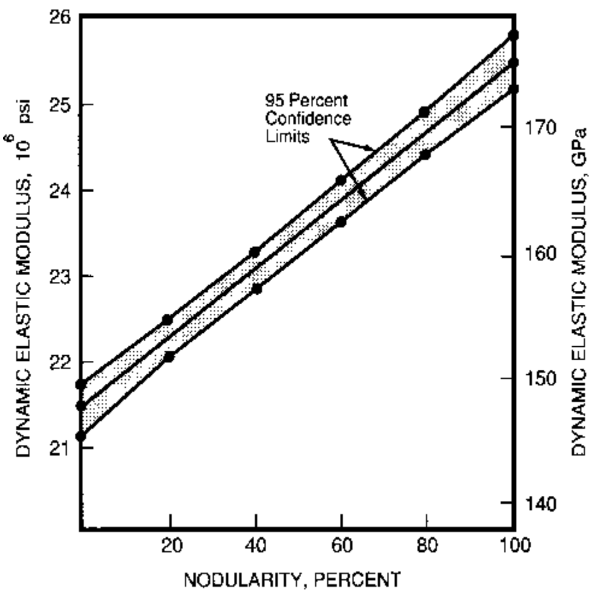
Ductile iron as a technologically useful material is used for manufacturing critical components in different industrial sectors viz., automobile and wind energy. Many investigators have examined its mechanical performance under a wide range of conditions where as others have attempted to explain its solidification behaviour and the many variables which affects in producing an acceptable product. Ductile iron is characterized by its unique properties (exhibits good combination of strength and ductility) and thus ensures its huge applications in heavy engineering industry. This is due to very typical microstructure and also owing to its melt chemistry, heat treatment, processing variables. Some lists of important factors which are responsible for its typical mechanical properties are discussed below.

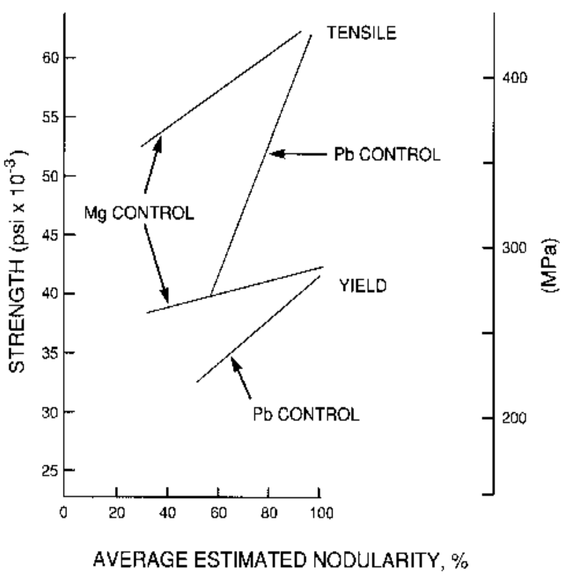
3.5.31 Effect of Graphite Shape, Volume & Graphite Distribution

Comparison of mechanical properties of ductile and gray cast iron establishes a wide difference in the said properties of the two materials. This refers to the nodularity which plays a significant role in determining properties within the ductile iron family. It has been evident from the literatures that nodularity and the morphology of the nonspherical particles produced as nodularity decreases, exerts a strong influence on the yield and tensile strengths of ductile iron. When nodularity is decreased by reducing the amount of residual magnesium (the most common spheroidzing agent used in commercial ductile iron) the nodules become elongated, but do not become sharp or 'spiky'. The result is a 10% decrease in yield strength and a 15% decrease in tensile strength when nodularity is reduced to 30%. Small addition of lead reduce nodularity by producing inter granular networks of spiky or plate-like graphite which results in dramatic reductions in tensile properties.

The effect of nodularity on pearlitic ductile irons can be determined by comparing the tensile properties, at constant carbide levels, of irons with nodularities 90, 70 and 40%. The pearlitic iron is more sensitive to loss in nodularity than its ferritic counterpart. At low carbide levels typical of good quality ductile iron, there is relatively little loss of strength as the nodularity decreases to 70% but as nodularity deteriorates further, strength decreases more rapidly. The amount and form of graphite in ductile iron can be determined during solidification and cannot be altered by subsequent heat treatment [75].

Designers can virtually eliminate the effect of nodularity on tensile properties by specifying that the nodularity should exceed 80-85% and that there should be no intercellular flake graphite. These criteria can be met easily by good production practices which ensure good nodularity through Mg control and prevent flake or spiky graphite by a combination of controlling flake-producing elements, their effects through the use of small additions of cerium. The distribution of the graphite nodules can have an effect on the overall matrix structure. If the nodules are very fine and uniformerly distributed, a large percentage of ferrite is found in the structure. On the other hand, if the nodules are large and widely spaced, pearlite or even carbide can grow in the intermolecular regions to affect the overall structure and mechanical properties. Figure 3.5.31a and 3.5.31b showing the effect of nodularity on dynamic elastic modulus and strength respectively.





(Fig. 3.5.31a) (Fig.3.5.31b)

Figure 3.5.31a: Relationship between Dynamic Elastic modulus and nodularity

(http://www.ductile.org/didata/Section3/Figures/pfig3_10.htm) dt.15/03/2015.

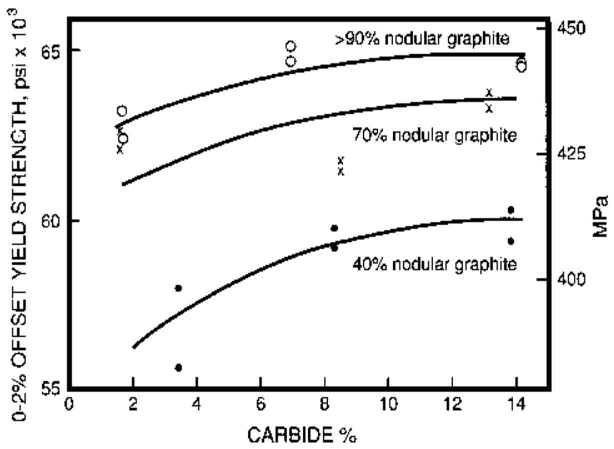
Figure 3.5.31b: Effect of Mg-controlled and Pb-controlled nodularity on yield and tensile strengths of ferritic Ductile Iron

(http://www.ductile.org/didata/Section3/Figures/pfig3_11.htm.) dt.15/03/2015.

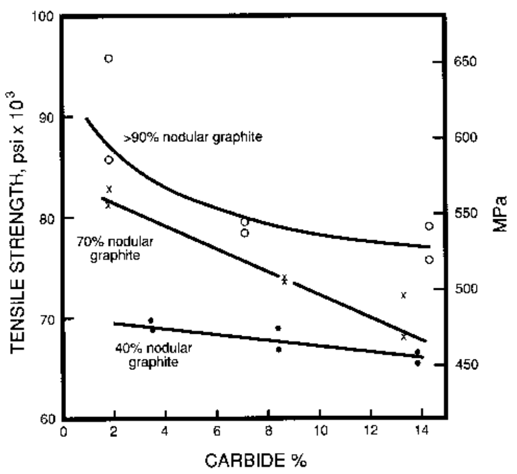
3.5.32 Effect of carbide in the Structure

Carbide content has both direct and indirect effect on the mechanical properties of DI castings. It is known that ductile iron castings are more prone to contain carbides than flake-graphite castings of similar section and size and carbon and silicon contents. This is partly because of the nature of spherodizing elements (magnesium and/or cerium) which promotes the formation of eutectic carbide and partly due to the fact that sequence of solidification produced by the growth of nodular graphite tend to promote under cooling during solidification to temperatures at which white iron structure as likely to form. Carbides in ductile irons can occur in three forms:

Eutectic carbide (or chill) results mainly from the rapid solidification and is most prevalent in corners and thin sections. Inadequate inoculation, low carbon and in particular low silicon and the presence of carbide promoting elements increases the likelihood of carbides being present in the structure. Inverse chill, which has fine acicular form, occurs at or near the heat centre of a casting section. The geometry of the casting and method of running the casting are important variables and the problem is often only solved by re-positioning or altering the size of ingates to change the pattern of solidification of casting.



(Fig 3.5.32a)



(Fig 3.5.32b)

Figure 3.5.32a: Effect of nodularity and carbide content on yield strength of pearlitic Ductile Iron.

(http://www.ductile.org/didata/Section3/Figures/pfig3_12.htm)dt.15/03/2015

Figure 3.5.32b: Effect of nodularity and carbide content on tensile strength of pearlitic Ductile Iron

(http://www.ductile.org/didata/Section3/Figures/pfig3_13.htm)dt15/03/2015

Segregation of carbides is more prevalent in heavy sections. They occur in the eutectic cell boundary area where the segregation of trace amounts of carbide-forming elements such as manganese or chromium occurs. These carbides do not readily respond to break down by heat treatment. The presence of carbide in ductile iron is undesirable for a number of reasons:

- It increases the tendency to form shrinkage porosity and thus increases the feeding requirements during casting.
- It increases the risk of cracking during knockout and fettling.
- It decreases the ductility of the iron.
- It drastically reduces the impact resistance.
- It increases hardness and reduces machinability.
- It requires treatment at 900-920^{o}C to remove the carbide.

The occurrence of all the three forms of carbide is minimized by efficient inoculation giving high nodule number and also by maintaining the contents of carbide promoting elements at low level. High silicon levels are also beneficial but the potential embrittling action of silicon contents above about 2.6% should not be overlooked. The formation of carbides thus increases the like hood of internal porosity of the castings by reducing the expansion effects produced by the formation of graphite during solidification. In order to minimize the detrimental effects of carbide on the properties and machinability of ductile irons, the carbide level should be less than 5% which be maintained by using high quality of pig iron in the melt followed by good inoculation practices [75].

3.5.33 Effect of Nodule Count

The number of graphite nodules present in a specific area of metal is called nodule count. Generally the quantity of nodules in an area of one square millimetre on a polished surface examined under a microscope at 100X magnifications is considered for nodule count. A graphite particle having length of two or more times its diameter cannot be considered as a nodule. Identification of nodules is a part of nodularity rating, ranging from 0 to 100%. When all nodules are completely of round shape, the state is called 100% rating irrespective of the actual number of nodules. Nodule count has the following effects on microstructure of the DI and plays important role influencing the mechanical properties. Nodule count determines the quality of iron. An optimum nodule count is required for quality.

- Nodule count influences the pearlitic content of as-cast ductile iron. With increase in nodule count, the pearlite content decreases resulting there is decrease in strength and increase in elongation.
- Presence of carbide in the microstructure is also affected by nodule count. Increasing the nodule count improves tensile strength, ductility and machinability by reducing the volume fractions of chill carbides, and carbides associated with 'inverse chill'. As the nodule count increases, the structure and properties become more uniform, segregation is reduced and carbides generally will be minimised [75].
- Matrix homogeneity is influenced by nodule count. Increasing the nodule count produces a finer and more homogeneous microstructure. This refinement of the matrix structure reduces the segregation of harmful elements which might produce intercellular carbides, pearlite or degenerated graphite.

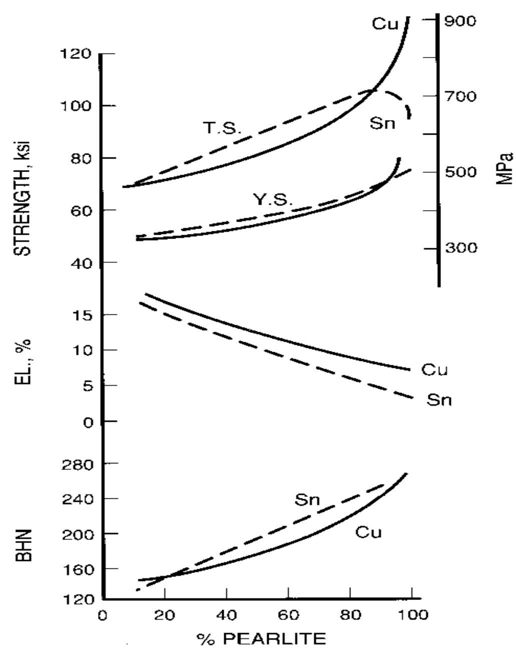
- Nodule count affects graphite size and shape. Increasing nodule count results in a decrease in nodule size which improves tensile, fatigue and fracture properties. Inoculation practices used to improve nodule count often make the nodules more spherical. Thus, high nodule count is generally associated with improved nodularity.

- Nodule count varies with the charge materials, alloy additions and metal processing including treatment and inoculation. Sulphur levels in the base iron are also very important. A minimum of 0.008% sulphur should be maintained. Lower sulphur levels may result in formation of more carbides and low nodule counts.

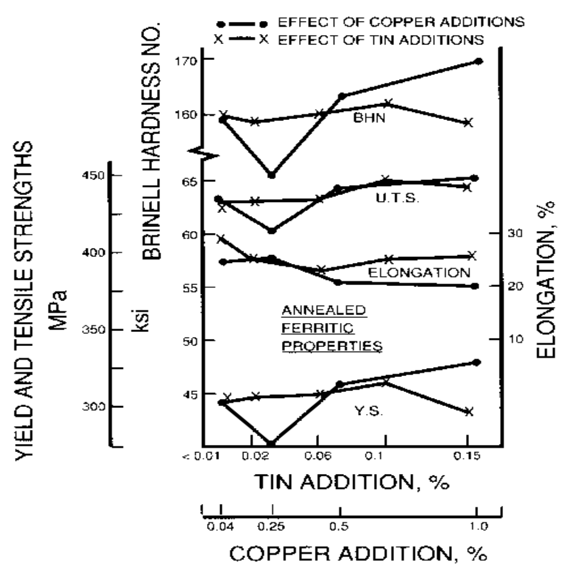
3.5.34 Effect of Matrix

No discussion on SG iron can be completed without a description of matrix properties and characteristics. The advantage of ductile irons over all other types of irons is that since the graphite is present as spheroids rather than flakes, it plays comparatively minor role in overall strength. Ductile irons therefore act like steels, with the matrix characteristics dominating the overall mechanical properties. The effects of the pearlite and ferrite ratios then become important and all conditions which affect this ratio will alter the mechanical properties. There are three variables viz., the cooling rate as the alloy passes through the eutectoid temperature, alloying additions which alter the phase proportion of the ferrite and pearlite and the distribution of graphite nodules which dominate the mechanical properties.

For the most common grades of Ductile Iron, the matrix consists of ferrite and/or pearlite. Ferrite is the purest iron phase in Ductile Iron. It has low strength and hardness, but it exhibits high ductility and toughness and good machinability. Pearlite is an intimate mixture of lamellar cementite in a matrix of ferrite. Compared to ferrite, pearlite provides a combination of higher strength and hardness and lower ductility. The mechanical properties of ferrito-pearlitic ductile Irons are, therefore, determined by the ratio of ferrite to pearlite in the matrix. This ratio is controlled in the as-cast condition by controlling the composition of the iron, taking into account the cooling rate of the casting. It can also be controlled by an annealing heat treatment to produce a fully ferritic casting, or by normalizing to maximize the pearlite content. The exceptional as-cast properties of the fully ferritic base material such as 455 Mpa UTS, 310 Mpa YS and 26% elongation for a Quality Index of 113: - are noteworthy. The Quality Indices of the samples, which were taken from different step bars, ranged from 90 to 113.



(Fig 3.5.34a)



(Fig 3.5.34b)

Figure 3.5.34a: Relationship between tensile properties and pearlite contents of as-cast Ductile Iron.

(http://www.ductile.org/didata/Section3/Figures/pfig3_15.htm)dt15/03/2015

Figure 3.5.34b: Tensile properties of annealed (ferritic) Ductile Irons with different Cu and Sn contents.

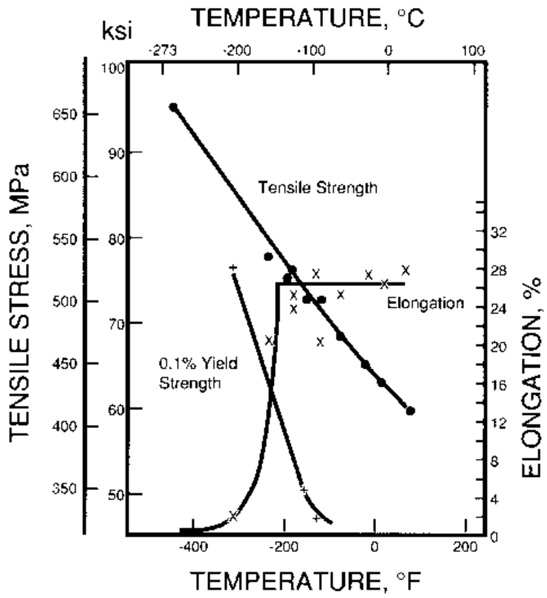
(http://www.ductile.org/didata/Section3/Figures/pfig3_17.htm)dt15/03/2015

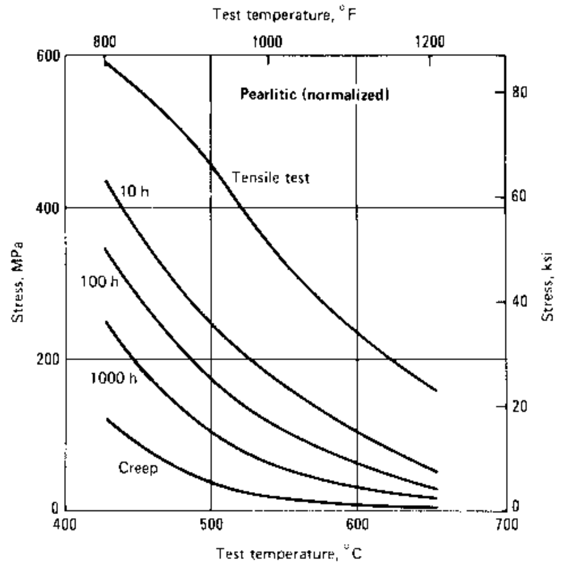
For alloy levels approaching and exceeding the amount required to produce a fully pearlitic matrix, additions of Cu and Sn have opposite effects. Additions of copper to a fully pearlitic matrix in the Cu-Mn alloy results in further increases in both yield and tensile strengths, probably due to solid solution strengthening. Additions of tin to the fully pearlitic Sn-Mn alloy do not affect the yield strength, but results in a decrease in tensile strength that has been related to the formation of intercellular degenerate graphite [75, 85].

3.5.35 Effect of Temperature on Tensile properties and Design Stresses

Ductile irons are structurally stable at low temperature and ferritic grades of ductile irons are generally preferred for low temperature applications because their ductility at low temperatures is superior to that of pearlitic grades. For an annealed ferritic ductile iron, with the decrease in temperature both yield strength and tensile strength increases. The room temperature elongation of 25% is maintained to very low temperature. Pearlitic grades of ductile iron exhibits a significantly different response to tensile properties with decrease in temperature. The yield strength increases where as tensile strength and elongation decrease. So pearlitic irons should be used with a caution at low temperatures.

Ductile Irons are also used for high temperature applications in terms of critical components for a long run. Unalloyed ductile irons retain their strength at moderate temperature where as alloyed ductile irons exhibits better resistance to deformation, growth and oxidation at high temperatures. The only high temperature applications in which Ductile Irons, with the exception of Type D-5 Ductile Ni-Resist, do not perform well are those involving severe thermal cycling. When determining design stresses for a Ductile Iron component, the designer must be aware of both the temperature range in which the component will be operated and the effect of temperature on tensile properties.





(Fig 3.5.35a)

(Fig 3.5.35b)

Figure 3.5.35a: Effect of temperature on the low-temperature properties of ferritic Ductile Iron.

http://www.ductile.org/didata/Section3/Figures/pfig3_19.htm(dt 15/03/2015)

Figure 3.5.35b: Tensile creep ruptures and creep behaviour of pearlitic Ductile Iron.

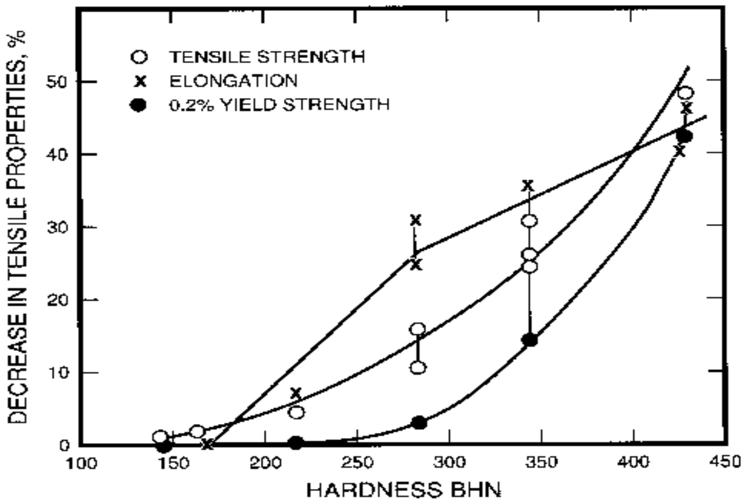
http://www.ductile.org/didata/Section3/Figures/pfig3_22.htm(dt15/03/2015)

The increase in yield strength with decreasing temperature for both ferritic and pearlitic Ductile Irons suggests that higher design stresses may be used at low temperatures. Because most low temperature applications also involve performance at room temperatures, the room temperature yield strength must be used in the calculation of design stresses. However, the use of a yield strength-related design stress is acceptable for low temperature applications only when the applied stress state can be simulated by a quasi-static (low strain rate) test. In such cases, both ferritic and pearlitic grades may meet the design criteria. If the application involves impact loading, or if good notch toughness is specified, selection should be limited to ferritic grades. For special low temperature applications requiring maximum elongation and toughness, annealed ferritic grades should be used. For temperatures up to 575^{o}F (300^{o}C), static design stresses can be based on the room temperature yield strength, as described earlier in this section. For temperatures above 650^{o}F (350^{o}C), design stresses should be related to creep data for applications in which dimensional accuracy is critical or stress rupture data when deformation can be tolerated but time-to-failure is critical [2, 3, 75].

3.5.36 Effect of Environment on Tensile Properties

When the ductile iron is exposed to ambient temperature for a long period, the tensile properties of certain grades of ductile Iron is reduced significantly. It is also known that, high strength ductile irons in contact with liquids such as water or motor oil (exposure to certain environments), may show a loss of ductility in the standard tensile test. This is resulted from liquid metal embritlement caused by of chemisorptions of embtirrling atoms at the crack tip leading to a reduction in the bond strength. Figure 3.5.36 summarizes the effects of exposure for 30 days to air-saturated, distilled water on the tensile properties of Ductile Iron samples with different hardness levels. Yield strength is not affected by exposure until hardness exceeded 275 BHN, above which it decreases rapidly, attaining a loss of over 40% at a hardness of 430 BHN. Tensile strength and elongation followed similar trends, but the loss of strength and ductility began at lower hardness levels (175 BHN) and increased more slowly, attaining the same level of reduction (40%) at 430 BHN. Figure 3.5.36 indicates that exposure to water for 3024 days has no significant effect on the tensile properties of ferritic Ductile Irons, but those quenched and tempered to produce hardness levels above 250 BHN are embrittled to a degree which increases with hardness. Embrittlement may be due to a hydrogen-related phenomenon similar to that occurring in high strength steels.

In case of embrittlement of ductile iron when subjected to certain environments, the reduction in the normal ductility may occur due to a physical or chemical change. Some common examples are blue brittleness, hydrogen embrittlement and temper brittleness. This phenomenon implies that there are changes happening within the metal structure, this definition can be extended to embrittlement resulting from changes generated by the interaction between the metal and its environment. These types of embrittlement are: hydrogen embrittlement, stress-corrosion cracking and liquid metal embrittlement [34, 75].



(Figure 3.5.36)

Figure 3.5.36: Degradation of tensile properties of Ductile Irons with different hardness levels after exposure to water for 30 days.

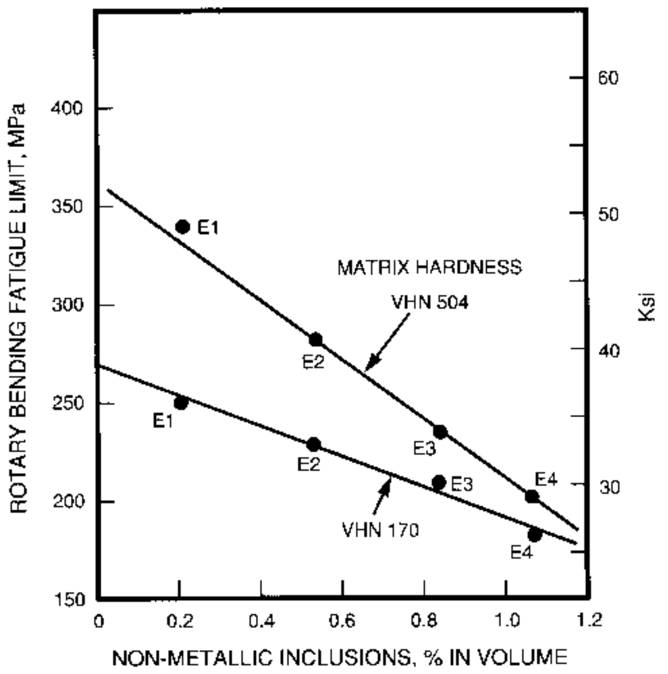
http://www.ductile.org/didata/Section3/Figures/pfig3_24.htm(dt15/03/2015)

3.5.37 Effect of Metal cleanliness

When the ductile iron is subjected to bending and torsional fatigue conditions in which the cyclic stresses reach a maximum at the component surface, the fatigue strength get reduced due to the presence of inclusions, dross, and other surface defects which act as crack initiation sites. Figure 3.5.37 shows that with the increase in the volume fraction of non-metallic inclusions, the fatigue strength significantly decreases. The influence of non-metallic inclusions on fatigue strength increases as matrix hardness increases. The increasing tendency use of Ductile Iron for various industrial critical components with as-cast surfaces, places an increased importance on the elimination of surface defects for applications requiring optimum fatigue strength.

The dross-related surface defects can be reduced by using filters in the mould filling system which results in a 25 per cent increase in fatigue life, as shown in the use of good foundry practices, including minimizing residual Mg content, careful de-slagging of ladles, good gating and pouring practices, the use of filters in the gating system and the reduction of the effects of flake-forming elements in both the metal and moulding materials, can result in better fatigue strengths for as-cast surfaces.

Ductile irons contain a host of impurities which deleteriously affect graphite structure and the subject has been intensively investigated by many workers. The important impurities like sulphur, oxygen and titanium in magnesium treated alloy have been shown to interfere with the crystallization process due to their surface active nature and should be maintained at a level less than 0.02%. However the deleterious action of these impurities can be reduced by increased amount of Mg and Ce [85].



(Fig 3.5.37)

Figure 3.5.37**:** Effect of matrix micro-hardness and volume fraction of inclusions on fatigue limit of Ductile Iron.

(http://www.ductile.org/didata/Section3/Figures/pfig3_30.htm)dt16/03/2015.

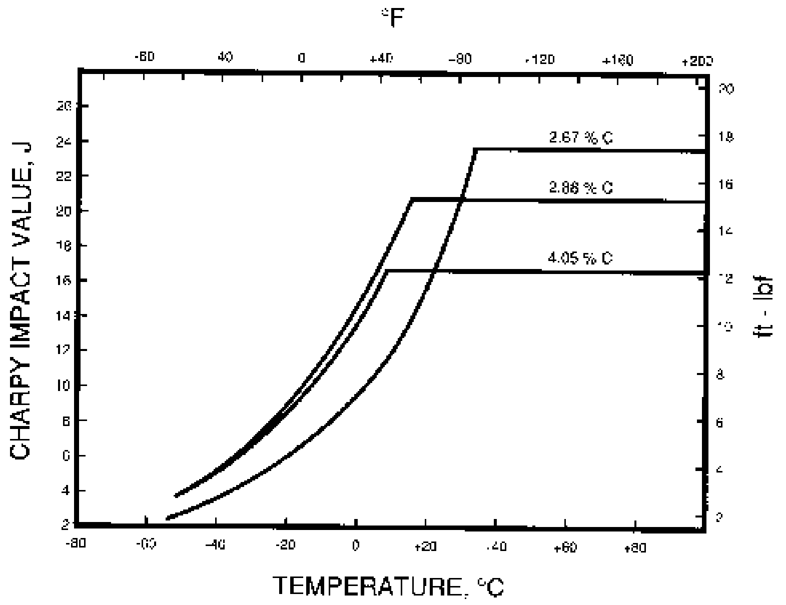
3.5.38 Effect of melt Chemistry

The physical properties of the ductile irons viz., density, thermal expansion, thermal conductivity, specific heat, electrical conductivity, magnetic properties and acoustic properties are affected by micro constituents as well as melt chemistry. The influence that the different microstructural constituents exert different local conditions also affects the mechanical properties of the ductile iron. It may be noted that increasing the silicon content from zero to 13.5% reduces the density of ferrite from 7.86 to 7.23 grams per cubic centimetre. Similarly the addition of chromium and particularly molybdenum raises the density of iron carbide.

Almost all elements present in trace amounts combine to reduce ferrite formation, and high-purity charges must be used for irons to be produced in the ferritic as-cast condition. Similarly, all carbide forming elements and manganese must be kept low to achieve maximum ductility and low hardness. Silicon is added to avoid carbides and to promote ferrite as-cast in thin sections. The electrical, magnetic, and thermal properties of ductile irons are influenced by the composition of the matrix. In general, as the amount of alloying elements increases, thermal conductivity deceases.

(A) Carbon (Graphite)

Ductile iron is defined as a high carbon containing, iron based alloy in which the graphite is present in compact, spherical shapes rather than in the shape of flakes, the latter being typical of gray cast iron. Higher is the carbon more is the graphite formed and lower are the mechanical properties. Carbon lowers the melting point of metal and thus acts as a graphatiser to favour the formation of gray cast iron. As the amount of graphite increases in the melt, there is relatively small decrease in strength, elongation, modulus of elasticity and in density. In GGG-50 ductile iron (ISO Grade) carbon requirement is 3.4-3.6% in the final casting, for sufficient graphitization (nodules) to take place. In the bath it should be 3.7-3.8% carbon to produce the product containing 3.5% carbon, as it is due to the loss taking place in solidification and in carbide formation.



(Fig 3.5.38a)

Figure 3.5.38a: Effect of carbon content on the v-notched Charpy energy of

ferritic Ductile Iron.

(http://www.ductile.org/didata/Section3/Figures/pfig3_42.htm)dt16/03/2015

In addition to influencing microstructural characteristics such as ferrite: pearlite ratio and carbide content, composition also affects the fracture behaviour of annealed ferritic Ductile Iron. The influence of carbon content on notched impact properties is primarily on the upper shelf energy, which decreases with increasing carbon content, as shown in Figure 3.5.38a. [75].

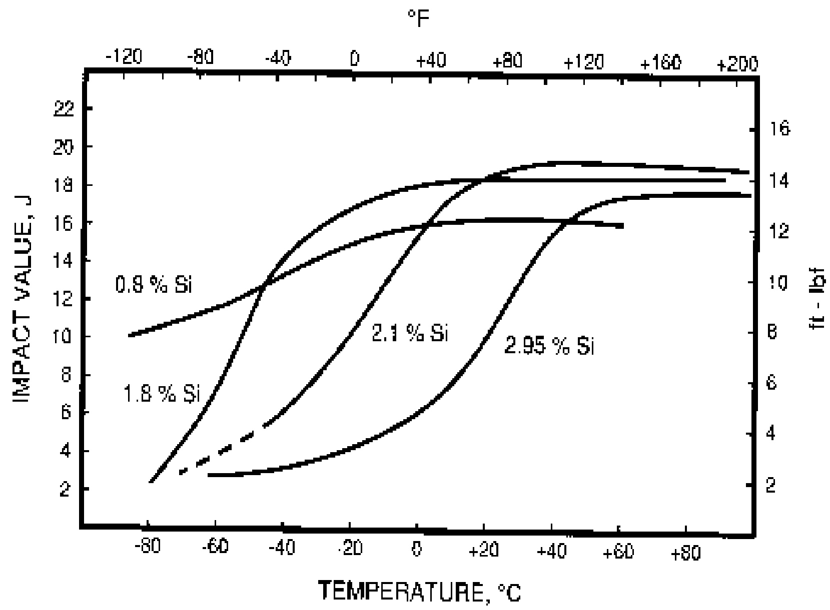
(B) Silicon

Silicon is a strong graphitizer. It exerts greatest controlling effect on the relative properties of combined carbon and free graphite and thus controls the properties of ductile irons. The Fe-C-Si system is composed of two eutectic temperatures, an upper stable temperature delimiting where carbon precipitates as graphites and a lower metastable one where carbon precipitates as iron carbide. The temperature interval between the two regions is an important parameter in determining the as-cast structure. Since silicon increase the separation between the two lines it acts as a graphitizer. As a consequence a low silicon nodular iron is usually dominated by iron carbide.

Silicon enhances the performance of ductile iron at elevated temperature by stabilizing the ferritic matrix and forming the silicon rich surface layer, which inhibits the oxidation. Stabilization of the ferrite phase reduces the high temperature growth in two ways. First, silicon raises the critical temperature at which ferrite transforms to austenite. The critical temperature is considered to be the upper limit of the useful temperature range for the ferritic ductile irons. Above this temperature the expansion and contraction of the surface oxide layer occur that reduces oxidation reduction. Then the strong ferritizing tendency of silicon stabilizes the matrix against the formation of carbides and pearlite, thus reducing the growth associated with the decomposition of these phases at high at high temperature.

So it is required in the acceptable range of "1.5-2.5", because if the %age composition of Si is more than 2.5, there will be appreciable decrease in the impact value. The oxidation protection offered by Silicon increases with increasing silicon content. Silicon levels above 4% are sufficient to prevent any significant weight gain after the formation of initial oxide layer. The potentially objectionable influences of increasing silicon content are: (1). Reduced impact energy. (2). Increased impact transition temperature. (3). Decreased thermal conductivity. Si is used to promote ferrite and to strengthen ferrite. So Si is generally held below 2.2% when producing the ferritic grades and between 2.5% and 2.8% when producing pearlitic grades.

The strong influence of silicon on the ductile-brittle transition temperature of ferritic Ductile Iron is shown in Figure 3.7. This Figure indicates that, to optimize low temperature toughness, silicon contents should be kept as low as possible. The successful production of as-cast carbide-free, low silicon Ductile Iron with a fully ferritic matrix requires high purity charge materials to minimize pearlite and carbide forming elements, controlled melting, holding and treating practices, and highly effective inoculation to maximize nodule count. The reduction in silicon level reduces both the yield and tensile strengths of the ferritic iron, and an offsetting addition of a less harmful ferrite strengthening element (such as nickel) is then needed to meet strength requirements. As with carbon, other considerations, especially microstructural control, require final silicon levels above 2% [78-79].



(Fig 3.5.38b)

Figure 3.5.38b: Influence of silicon content on the v-notched Charpy energy

of ferritic Ductile Iron.

(http://www.ductile.org/didata/Section3/Figures/pfig3_43.htm) dt16/03/2015.

(C) Manganese

Manganese has more affinity for sulphur than iron and it is present in the melt in the form of MnS. Manganese is a mild carbide forming element. The amount of Mn which combines with sulphur to form MnS particles in liquid iron and rises to the top of the melt has to be removed. Manganese has strong cementite-stabilising effect on eutectoid graphitization. MnS has no effect but removes the red shortness effect of Fe-FeS. The decomposition of austenite to ferrite plus graphite or to pearlite in spheroidal graphite (SG) cast iron is known to depend on a number of factors among which are the nodule count, the cooling rate, and the alloying additions (Si, Mn, Cu, etc.).The detrimental effect of Mn on the growth kinetics of ferrite during the decomposition of austenite in the stable system is explained in terms of the driving force for diffusion of carbon through the ferrite ring around the graphite nodules. Finally, it is found that copper can have a pearlite promoter role only when combined with a low addition of manganese.

As it is a mild pearlite promoter, with some required properties like proof stress and hardness to a small extent, Mn retards the onset of the eutectoid transformation, decreases the rate of diffusion of C in ferrite and stabilizes cementite (Fe3C), but the problem here is the embrittlement caused by it, so the limiting range would be 0.18-0.5%. The global manganese content of a ductile iron casting depends on the weighted chemical analysis of the metallic charge. The effect of excess manganese content in the cast melt causes segregation effect which occurs at the grain boundaries and deteriorates the casting quality. The recommended maximum manganese level in heavy section ductile iron casting is 0.30% [75, 78].

(D) Copper

The influence of copper is complex and depends upon whether the iron contains subversive elements such as titanium, in which case even as little as 1% copper can cause the formation of substantial amount of flake graphites. The effect of various additions of copper and the cooling rate on the temperature of the onset of the stable and metastable eutectoid reactions describes the conditions for the growth of ferrite and of pearlite. These reactions can develop only when the temperature of the alloy is below the lower boundary of the ferrite/austenite/graphite or ferrite/austenite/cementite related three-phase field. Copper is a strong pearlite promoter. It increases the proof stress with also the tensile strength and hardness with no embrittlement in matrix. So in the pearlitic grade of the ductile iron the copper is kept between 0.4-0.8 percent and is a contaminant in the ferritic grade [3, 33].

(E) Nickel

The morphology of carbon is non-uniform and not easy to control. Recent research has taken considerable attention for the carbon material because of its high thermal and electrical conductivity, corrosion resistance and lubricating ability. It helps in increasing the U.T.S without affecting the impact values .So it can be used in the range of 0.4-2.0%. It strengthens ferrite, but has much less effect than Silicon in reducing ductility. As a Mild pearlite promoter, increases proof stress but little effect on tensile strength, but there is the danger of embrittlement with the large additions, in excess of 2%. Due to the high cost it is generally present as traces in the matrix. The irons treated with nickel have nodular graphite in a matrix of austenite with rather more carbide than the untreated irons [42].

(F) Molybdenum

It is a mild pearlite promoter. It forms intercellular carbides especially in heavy sections. Increases proof stress and hardness. It enhances the danger of embrittlement and gives low tensile strength and elongation values.

(G) Chromium

It prevents the corrosion by forming the layer of chromium oxide on the surface and stops the further exposition of the surface to the atmosphere. But as it is a strong carbide former so not required in carbide free structure and <1% required in the grade of GGG-50(ISO Grade) .it is kept around 0.05% Maximum. As a very strong carbide former, it should not be employed if carbide free structure is required.

(H) Magnesium

Magnesium works as the modifier in the matrix and nodularises the graphite, increases the ductility and yield strength. Regardless of which process is used, the magnesium treatment must be done by using residual magnesium content in the range 0.04 – 0.05%, together with low final sulphur contents (Less than 0.01%). Failure to obtain satisfactory levels of residual magnesium can be caused by one or more factors of those mentioned below.

- Excessive treatment temperature leading to high volatilization losses of magnesium.
- Inaccurate weighing of the treatment alloy, the liquid metal being treated of both.
- Loss of magnesium (Fading) – ladle treated metal should be poured within 10 minutes of the magnesium treated alloy used.

Recent works at BCIRA has led to the development of a rapid foundry shop floor test based on thermal analysis. In Mg treated irons, high Mg content acts to promote carbidic microstructures and increase shrinkage. The magnesium level must be controlled carefully to the cooling rate of the casting to avoid increased chilling tendency. This cooling rate is described as proportional to the modulus, which is a ratio of casting volume to cooling surface area. Thus modulus is a more accurate way to describe the cooling of a casting section than just measuring the section size. Obviously all of the carbide stabilizing elements should be kept to relatively low levels to minimize their effect on chill formation. This will then allow most of the available carbon to transform into graphite [86].

(I) Sulphur and Phosphorous

Sulphur retards graphitization and increase the size of the flakes. High sulphur tends to reduce fluidity and is often the cause of formation of blowholes in castings. The presence of Sulphur gives good machinability. The range of sulphur present in the ductile iron is from 0.009-0.015%. The larger amount of sulphur may cause the hot (red) shortness and increases the chances for dross formation in the casting during solidification.

Presence of phosphorous in the melt form iron phosphide (Fe_3P) which forms a ternary eutectic with cementite and austenite. The ternary eutectic is called steadite which is brittle and has a melting point of around 960°C. This increases the fluidity and extends the range of eutectic solidification and thus helps in primary graphitization. This increased fluidity also helps in giving good castability to the thin and intricate castings. Phosphorous is kept intentionally very low, as it is not required because it causes cold shortness and so the property of ductile iron will be affected adversely [75, 78].

(J) Tin

Tin is a strong pearlitie former. There is a progressive increase in the amount of pearlite with increasing additions of tin. This is accompanied by a progressive increase in tensile strength, elongation and hardness. The microstructure is perfectly nodular with no flake graphite. The allowed range of Tin percentage in the melt is from 0.05-0.1%, but if more than the specified range is found in the ductile iron casting, then it will increases proof stress and hardness but will enhances the danger of embrittlement giving low tensile strength and elongation values.

(K) Arsenic

Arsenic is seen to have an effect very similar to tin, but at least twice as much arsenic is required to achieve the same degree of pearlite stabilization as that of given amount of tin. It is also clear that at least 0.09% arsenic can be tolerated without harmful effect on the formation of nodular graphite. Depending on the type of requirement of nodular iron, both arsenic and tin are to be considered subversive elements. If the aim is to produce a high strength iron with a pearlitic matrix, these elements may be ignored, but if the aim is to produce a relatively soft iron of good ductility, either in the as-cast condition or after heat treatment , then the amounts of tin and arsenic must be kept to a minimum. The introduction of cerium may slightly offset the pearlite stabilizing effect of arsenic. The influence of cerium is not pronounced, however, and is of doubtful practical value if large amount of arsenic are encountered.

(L) Antimony

Antimony has a harmful effect as that of lead and bismuth on the property enhancement of spheroidal graphite iron castings. The addition of antimony gives rise to residual antimony of about 0.004% which has a profound effect on the elongation property of the ductile iron. It should not be used for the commercial grade of SG iron production. Presence of small amount of antimony causes harmful effect on the production of ductile iron by magnesium. The tendency of pearlite formation in the metallic matrix is increased with increase of antimony. The microstructure contains small amount of flake graphites together with spheroidal nodules in a matrix containing considerably more amount of pearlite. Cerium is clearly capable of neutralizing the harmful effect of antimony, but the extent of neutralization depends upon the amount of residual cerium.

(M) Lead

Lead shows harmful effect on the mechanical properties of spheroidal graphite irons. If the liquid metal contains lead then cerium treatment is carried out to neutralize the effect of lead. It is observed that Pb when present in amount of 0.009%, its deleterious effect starts and for 0.011% Pb the nodules are completely converted into flakes. The harmful effect of lead also depends on the cooling rate of the casting. With rapid cooling, larger amounts of lead can be tolerated than with slow cooling. Thus a given lead content may only give a small amount of flake graphites in a relatively small section, whereas a completely flake graphite structure would be obtained in a relatively large section.

(N) Bismuth

The mechanical properties of ductile iron are also influenced by the harmful effect of bismuth. If the iron is treated with cerium and contains 0.006% bismuth, the flake like graphite structure is found with pearlite matrix and some amount of ferrite. It indicates that presence of 0.003% of bismuth in the melt causes a harmful effect whereas iron containing 0.006% of bismuth completely inhibit the nodular structure. The amount of bismuth which can be tolerated depends upon the cooling rate of the casting-larger amount of bismuth can be tolerated in rapidly cooled sections than in slowly cooled sections.

(O) Aluminium

Aluminium inhibits the formation of spherulitic nodules and causes the formation of flake graphite structures in the magnesium treated irons. Aluminium causes the retention of sulphur which in turn causes the formation of flake graphites. However, aluminium can have the harmful effect even when the sulphur contents are normal for the formation of nodular irons. The amount of aluminium up to 0.10% in the melt does not appear to influence the mechanical properties, but there is a strong drop in elongation value when the aluminium is about 0.13%. The harmful effect of aluminium can be neutralized by adding the required amount of cerium in the melt.

(P) Titanium

The influence of titanium on the properties of spheroidal graphite iron depends very considerably upon the magnesium content and the section size of the casting. The main source of the titanium is the foundry pig irons used for the production of ductile iron. The amount of titanium in the pig iron is capable of easy detection than any other subversive element. Cerium is capable of neutralizing the subversive effect of titanium. The addition of small amount of cerium has produced a remarkable improvement in the tensile strength due to the replacement of a mixed flake and nodular graphite structure by a completely nodular graphite structure.

3.6 Mechanical Properties of Ductile Iron

Introduction:

All materials always serve as an enabling technology for contributing to solutions in problems of concern to society in different ways of its introduction. The civil and environmental professionals can contribute to improve the quality of life by seeking solutions to infrastructure deterioration, hazard mitigation, structural safety, sustainability, environmental protection, and construction productivity. Now a days, there are several types of new and advanced materials are used for different critical applications, but still ductile irons are the materials of choice for design Engineers for its high strength to weight ratio and low cost of production. The fluidity tendency of the ductile iron and ease to cast complex shapes at relatively low cost with desired properties can be achieved by careful control over composition and cooling rate. Ductile irons are a material of confidence because of its unique properties. They possess good castability, damping capacity and mechanical properties and fair machinability. Owing to these advantages, ductile irons have been used in different sectors viz., automobile industry, Agricultural equipments, wind mill parts, and pipe industry etc., Some of important examples like Steering knuckles, hypoid rear axle gears, camshafts, crankshafts and disk-brake callipers are used in vehicles [34] .

The more use of ductile iron as critical components in all industrial sectors highlight its versatility and suggest many additional applications. In order to use ductile iron with confidence, the design engineer must have access to engineering data describing the following mechanical properties: elastic behaviour, strength, ductility, hardness, fracture toughness and fatigue properties. Physical properties like thermal expansion, thermal conductivity, specific heat, electrical conductivity, density, and magnetic and electrical properties are also of interest in many applications. This Section describes the mechanical and physical properties of conventional Ductile Irons, relates them to microstructure, and indicates how composition and other production parameters affect properties through their influence on microstructure [36, 75].

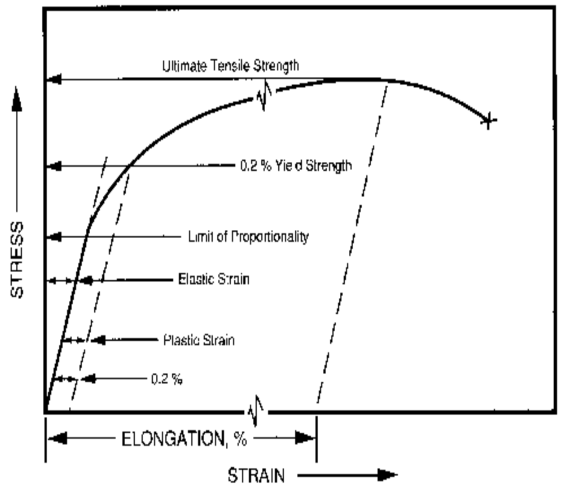
3.61 Tensile Properties

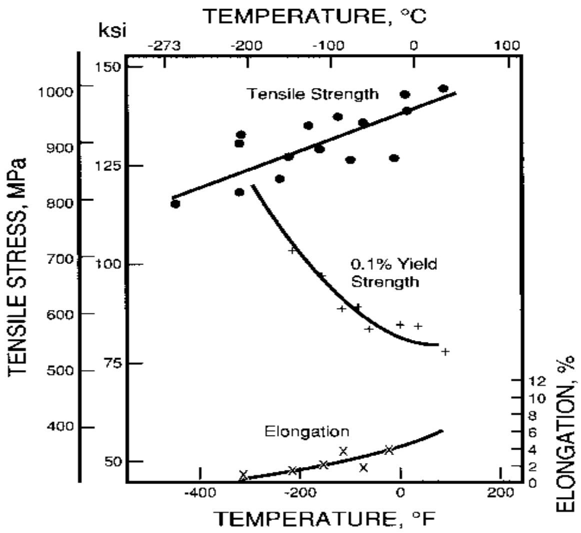
The discovery of Ductile Iron in 1948 gave a new engineering material which has better strength to weight ratio. This material is being used for manufacturing of critical components for industrial use. This material got a wide recognition as an economical choice for high performance complex ferrous parts. After fifty years of research and development, this material is introduced in the market. Its properties can be tailored for applications requiring high toughness, corrosion resistance or high tensile strength. The tensile properties of conventional Ductile Iron, especially the yield and tensile strengths and elongation, have traditionally been the most widely quoted and applied determinants of mechanical behaviour [86].

Tensile test is one of the most widely performed tests. Various properties of the material that can be determined by tensile test are yield stress, upper and lower yield points, tensile strength, elongation and reduction in area. The yield stress is defined as the stress at which plastic deformation of the tensile specimen takes place at a constant load [Fig.3.61a]. According to Hooke's law, there is a linear relationship between stress and strain at low tensile properties. The slope of the straight line is called modulus of elasticity or Young's modulus. Annealed or normalized mild steels exhibit elastic behaviour until the yield point, where plastic deformation occurs suddenly and without any initial increase in flow stress. In Gray Iron, the graphite flakes act as stress-raisers, initiating microplastic deformation at flake tips at very low applied stresses. This plastic deformation causes the slope of the stress-strain curve to decrease continually and as a result Gray Iron does not exhibit true elastic behaviour. Untile Iron exhibits a proportional or elastic stress-strain relationship similar to that of steel but which is limited by the gradual onset of plastic deformation. During tensile test of the specimen, the Poisson's Ratio is found with a little variation in ductile iron and the commonly accepted value is 0.275 [75].

At the proportional limit, the stress of the material is maximum and it exhibits elastic behaviour. When a material is subjected to stress below the proportional limit and the stress is then removed, the stress-strain curve remains to the origin. . There is no permanent change in dimension. When the stress exceeds the proportional limit, plastic strain reduces the slope of the stress-strain curve.

Upon removal of the stress, the strain decreases linearly, following a line parallel to the original elastic curve. At zero stress, the strain does not return to zero, exhibiting a permanent plastic strain, or change in dimension of the specimen (Fig.3.6b1). In Ductile Irons, which exhibit a gradual transition from elastic to plastic behaviour, the proportional limit is defined as the stress required producing a deviation from elastic behaviour of 0.005%. It is measured by the offset method used to measure the yield strength and may also be estimated from the yield strength. The ratio of proportional limit to 0.2% yield strength is typically 0.71 for ferritic grades, decreasing to 0.56 for pearlitic and tempered martensitic grades.





(Fig 3.61a) (Fig 3.61b)

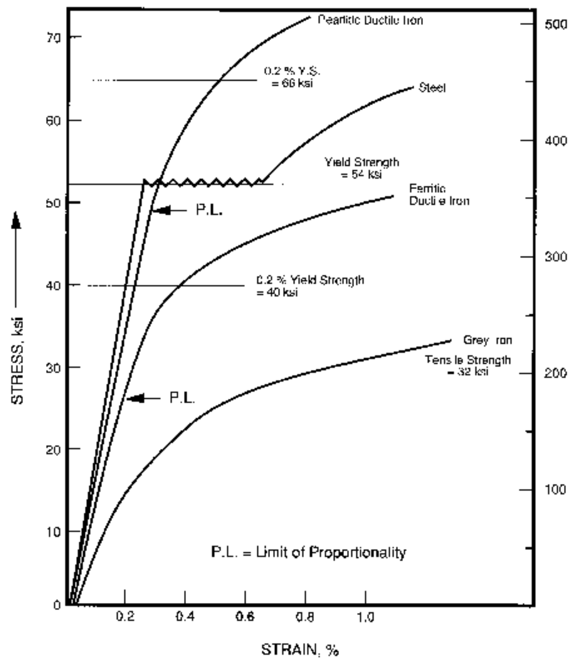
Figure 3.61a: Typical stress-strain curve for ductile metals.

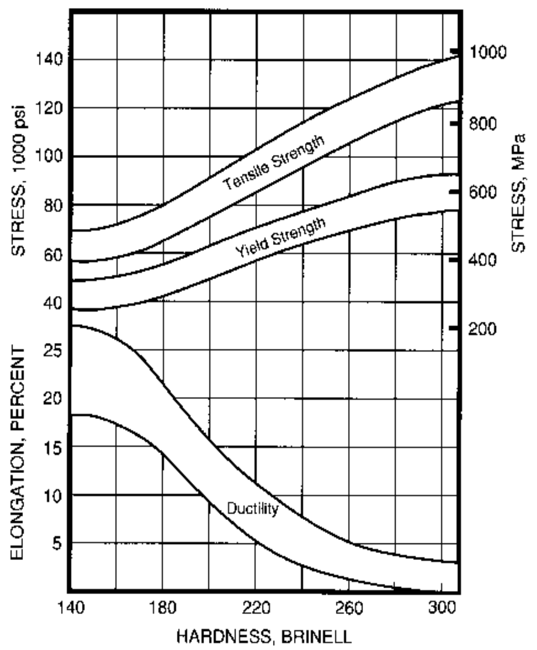
(http://www.ductile.org/didata/Section3/Figures/pfig3_2.htm) dt.17/03/2015

Figure 3.61b: Relationship between tensile Properties

(http://www.ductile.org/didata/Section3/Figures/fig3_20.gif)dt 17/03/2015.

The yield strength, or proof stress is the stress at which a material begins to exhibit significant plastic deformation. The sharp transition from elastic to plastic behaviour exhibited by annealed and normalized steels (Fig. 3.61c) gives a simple and unambiguous definition of yield strength. For ductile iron, the offset method is used in which the yield strength is measured at a specified deviation from the linear relationship between stress and strain. This deviation, usually 0.2 %, is included in the definition of yield strength or proof stress in international specifications and is often incorporated in the yield strength (YS) terminology.





(Fig 3.61c) (Fig 3.61d)

Figure 3.61c: Elastic and yielding behavior for steel, Gray Iron and ferritic and pearlitic Ductile Irons.

(http://www.ductile.org/didata/Section3/Figures/pfig3_3.htm)dt17/03/2015

Figure 3.61d: General relationships between tensile properties and hardness for Ductile Iron.

(http://www.ductile.org/didata/Section3/Figures/pfig3_1.htm)dt17/03/2015

The tensile strength, or ultimate tensile strength (UTS), is the maximum stress in tension which a material will withstand prior to fracture. It is calculated by dividing the maximum load applied during the tensile test by the original cross sectional area of the sample. Tensile strengths for conventional Ductile Irons generally range from 414 MPa for ferritic grades to over 1380 MPa for martensitic grades. Fig 3.61d shows general relationship between tensile properties and hardness of ductile iron. Although not specified, the modulus of elasticity and proportional limit are also vital design criteria. The modulus of elasticity for ductile irons, measured in tension, varies 162-170Gpa [75, 80].

3.62 Elongation

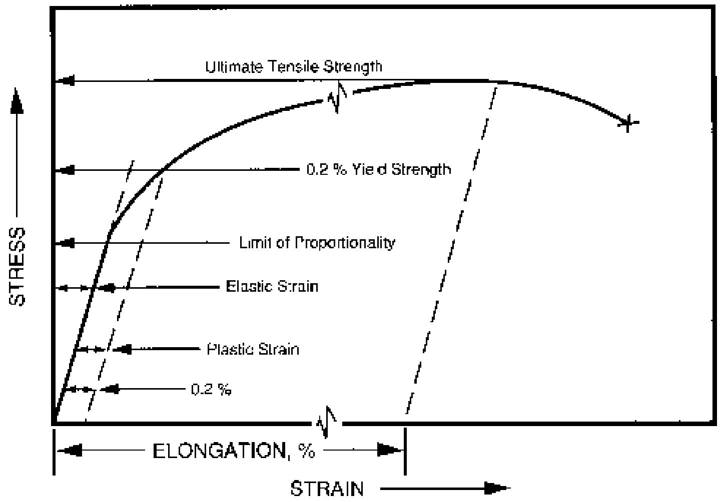
Ductile iron is characterized by having all of its graphite occur in microscopic spheroids. Although this graphite constitutes about 10% by volume of ductile iron, its compact spherical shape minimizes the effect on mechanical properties. The graphite in commercially produced ductile iron is not always in perfect spheres. It can occur in a somewhat irregular form, it may appear chunky as found in Type II in ASTM Standard A247. Elongation is generally reported as percentage of elongation. It is defined by change in length per unit length of the tensile specimen multiplied by 100. The change in length is always measured relative to some length marked on the tensile specimen prior to testing. The reference length is referred to as gauge length. Elongation is used widely as the primary indication of tensile ductility and is included in many Ductile Iron specifications. Although shown as the uniform elongation in figure 3.62, elongation also includes the localized deformation that occurs prior to fracture. However, because the localized deformation occurs in a very limited part of the gage length, its contribution to the total elongation of a correctly proportioned bar is very small. Brittle materials such as Gray Iron can fail in tension without any significant elongation, but ferritic ductile irons can exhibit elongation of over 25%.

Some grades of SG iron offer elongation figure in excess of 20%. Ductility and tensile strength are the major factors in determining the impact resistance of metals. Although it is clear that the ductility of a casting may be significantly different from the conventional test piece, the measure of ductility is a good relative index of plasticity. The commonly used index of ductility is the plastic elongation of a 2" test bar. A395 ductile iron is one of the most ductile of all cast irons and shows 18% to 30% elongation on a test piece.

An expression for the determining percentage of elongation is

Percentage elongation = {(Lt-L0)/L0}*100

Where Lt is the final length and L0 is the initial length (gauge length) [80].



(Fig 3.62)

Figure3.62: Uniform Elongation with localized deformation

(http://www.ductile.org/didata/Section3/Figures/pfig3_2.htm) dt. 17/03/2015

3.63 Hardness

The hardness of Ductile Iron is usually and best measured by the Brinell test, in which a 10 mm diameter hardened steel or tungsten carbide ball is pressed into a flat surface of the work piece. Hardness is expressed as a Brinell Indentation Diameter (BID) or a Brinell Hardness Number (BHN). The spheroidal graphite has a remarkable effect on the mechanical properties (Figure 3.63a and 3.63b) of DI. The hardness test of DI is very useful and directly related to other properties. The relation between tensile properties is dependable when the microstructure and chemical analysis are typical whereas the relation is independable when the graphite is very irregular or the matrix contains primary carbides. The hardness of all graphite irons is essentially the hardness of the matrix metal reduced to a somewhat lower value by the presence of the graphite. The Brinell test is preferred to determine the hardness of ductile iron castings. The typical Brinell hardness test uses a 10 millimetre diameter steel ball as an indenter with a 3000 kgf force. For softer materials, a smaller force is used. For harder materials, a tungsten carbide ball is used. Though Brinell hardness has the same unit as of pressure, it is expressed as a number without assigning any unit. The mathematical formula for BHN is given by

$$\mathrm{BHN} = \frac{2P}{\pi D\left(D - \sqrt{D^2 - d^2}\right)}$$

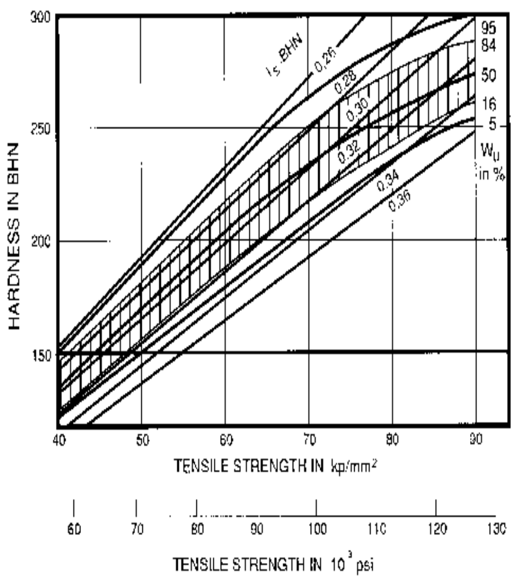
Where

P = applied load (kg)

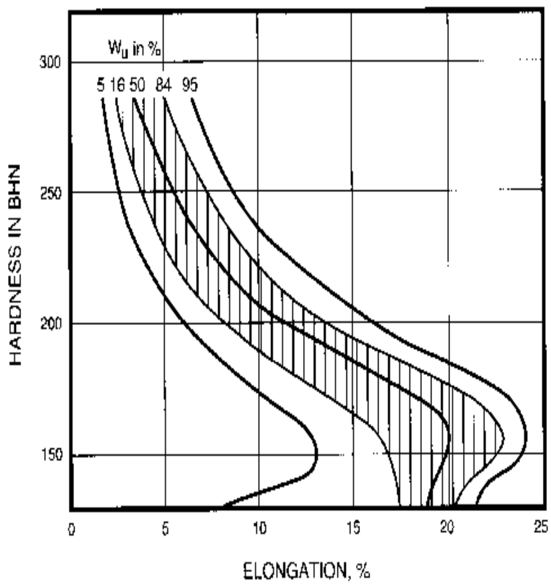
D = diameter of the indenter (mm)

d = diameter of the indentation (mm)

The BHN can be converted to ultimate tensile strength (UTS), although the relationship is dependent on the material and therefore determined empirically [80].



(Fig 3.63a)



(Fig 3.63b)

Figure 3.63a: Relationship between tensile strength and hardness of Ductile Iron

(http://www.ductile.org/didata/Section3/Figures/pfig3_7.htm) dt. 17/03/2015

Figure 3.63b: Relationship between elongation and hardness of Ductile Iron.

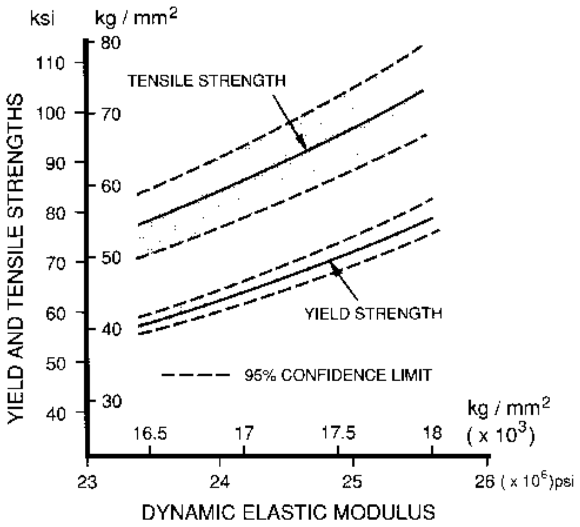
(http://www.ductile.org/didata/Section3/Figures/pfig3_8.htm) dt 18/0382015

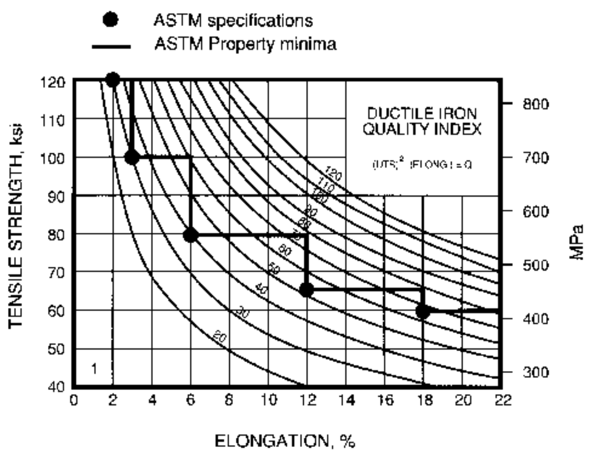
3.64 Relationships between Tensile Properties

The tensile properties of spheroidal graphite iron are tensile strength, yield strength and percentage of elongation. The minimums for these properties are typically established by the hardness values of the castings. Due to the infuence of spheroidal graphite, the tensile properties and the Brinell hardness of ductile iron are well related. The relation between tensile properties and hardness depends on microstructure and the metallic matrix. Since silicon being the ferrite promoter, the hardness and strength are dependent upon hardening of the ferrite by the elements dissolved in it.

Manganese and nickel are also common ferrite hardeners. Pearlitic matrix irons have lamellar carbide as the principal hardening agent.

A ductile iron with tempered martensite structure having uniform matrix shows higher strength to hardness relation. The acicular or bainitic matrix irons have the similar relation, but generally shows less ductility at a given strength. The properties of ductile iron are also affected to some extent by processing variables including inoculation, post inoculation, moulding materials, cooling rate and shakeout temperatures. Reduced cooling times in the mould and hot shakeout temperature increases strength because the castings are effectively normalized by this treatment. Fig 3.64a illustrates the non-linear least square relationship between tensile strength and the dynamic elastic modulus.





(Fig 3.64a)

(Fig 3.64b)

Figure 3.64a: Relationships between yield and tensile strengths and dynamic elastic modulus for Ductile Iron, (http://www.ductile.org/didata/Section3/Figures/pfig3_4.htm) dt.17/03/2015

Figure 3.64b: Relationship between Quality Index for Ductile Iron and ASTM Specification A536, (http://www.ductile.org/didata/Section3/Figures/pfig3_5.htm) dt. 17/03/2015

In 1970 Siefer and Orths, in a statistical study of the mechanical properties of a large number of Ductile Iron samples, identified a relationship between tensile strength and elongation of the form:

$$\textbf{(Tensile strength ksi)}^{2} \textbf{ x (elongation \%)} \div \textbf{1000 = Q}$$

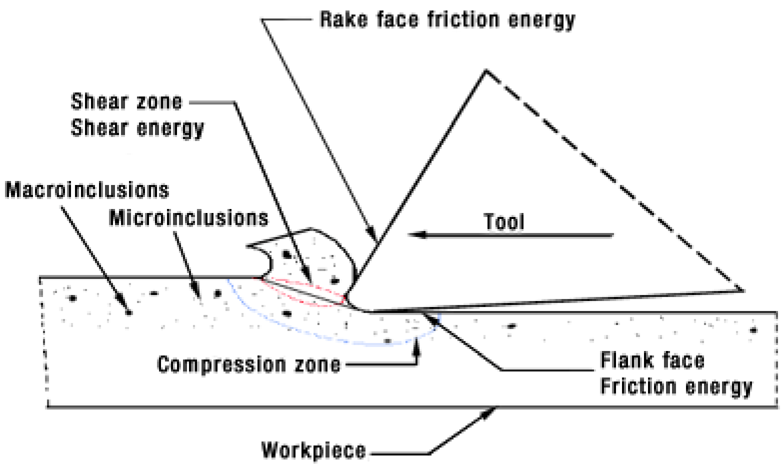
Where Q is a constant.

A larger value of Q indicates a combination of higher strength and elongation and, therefore, higher material performance. Crews (1974) defined Q as the Quality Index (QI) for Ductile Iron. Both the QI and the underlying relationship between strength and elongation offer valuable insights into the quality of different Ductile Iron castings and the feasibility of obtaining various combinations of properties (Fig 3.64b). High QI values have been shown to result from high modularity (high percentage of spherical or near-spherical graphite particles), absence of intercellular degenerate graphite, high nodule count, a low volume fraction of carbides, low phosphorus content (<0.03%) and freedom from internal porosity. High quality castings with these characteristics can be produced consistently by a competent, modern Ductile Iron foundry [75, 78-80].

3.65 Machining characteristic of ductile iron

Machinability is measured by determining the relationship between cutting speed and tools life. These two factors influence the machine tool productivity and machining costs. The machinability of ductile iron is dependent upon two factors viz., microstructure and hardness of the material. Presence of graphite influences the cutting force and surface finish whereas hardness depends upon microstructure of the DI. The constituents of the microstructure act as the primary determinant of the cutter tool life. In DI, the graphite is present as tiny ball not as flakes as in gray cast iron. These spheroids serve the same purposes of cheap breaking and lubrication in machining as flakes do for gray iron. Ductile iron has considerably higher tensile strength than gray iron at the same hardness, but the machinability is superior in some applications. Many factors are responsible for influencing tool life of machining iron. This includes graphite morphology, melt chemistry, ferrite to pearlite ratio, cooling rate from the eutectic through the eutectoid temperatures and the presence of either endogenous or exogenous inclusions. Several factors that influence machinability are illustrated in fig 3.65. The influence of microstructural components of the metallic matrix on the machinability of the DI is as follows:

Ferrite: It is the softest matrix constituent in the spheroidal graphite iron and exhibits the best machinability. This is due the effect of Silicon combined with ferrite which will decrease the toughness of ferrite. Machinability will increase when up to 3% Si is added, but if the Si content is even more then machinability will decrease.



(Fig 3.65)

Figure 3.65: Schematic representation of a Tool Advancing Through a Metal Part.

(http://www.atlasfdry.com/machinability.htm#figure1) dt. 18/03/2015

Pearlite: It consists of soft ferrite and hard lamellar iron carbide. The hardness and machinability of DI is determined by the volume fraction of the pearlite and the fineness of lamellae. This type of matrix is found in intermediate grades off ductile iron.

Carbide: It is basically very hard and shows poorest machinability. If carbide is present in thin lamella form in pearlite in the matrix of DI, then it can be sheared and made machinable, but some processes are available to offset the effect of carbide on machining characteristic of ductile iron.

Martensite: It is extremely hard matrix phase which is produced by quenching of ductile iron. Due to hardness and brittle characteristics, is not machinable. However, if martensite is tempered then it is easy for machining than pearlite or other matrix with similar hardness.

The machining characteristic of ductile iron is influenced by the graphite shape, matrix composition and the melt chemistry. The ductile irons are used in variety industrial applications because of good castability and excellent mechanical and physical properties. Ductile iron offers the designer all the manufacturing advantages of casting plus the added benefits of machinability (e.g. strength ratio which is superior to other cast irons and cast steels) [88].

3.7 Applications of SG Iron

The applications of SG irons have been increased tremendously in recent years. Due to the spheroidal form of graphite in ductile iron, it is not brittle like cast iron and therefore can be used where toughness and resistance to shock loading is required. The mechanical properties of DI is better than that of basic cast steel and are used as the alternative, whilst still offering acceptable service performance. Graphites also act as lubricant and improve wear resistance. The applications of ductile irons have been extensively used in the automotive industry where it can provide high strength and low cost alternatives to aluminium. Spheroidal graphite iron is used in applications where optimal impact, fatigue, electrical conductivity and magnetic permeability features are required. Typical application of SG iron includes moulds, dies, valves, pistons, engine crank shaft, brake calliper disc (brake anchor and brake anchor plate), machine tool bed, electric insulator post and cap, steering knuckle, rack and pinion of steering assembly, piston for impact drills, rolling mill-rolls, brake shoe for heavy duty brakes, glass moulds, spacer cage for rolling bearing, piston rings, wind mill items, agricultural and pipe line components etc. A brief description of DI applications in different sector has been mentioned below.

3.71 Automotive Applications:

The development of ductile iron technology allows the design engineers of energy consuming equipment to select the most appropriate material based on cost/material properties consideration. The automotive industry is the second largest ductile iron casting application field. Almost all crankshafts are being manufactured by ductile iron. Most of the worldwide cars are fitted with ductile iron crankshaft, instead of forged steel crankshaft. The following automotive ductile iron components are selected to illustrate the utilization of the mechanical and physical properties of various types of ductile irons.

(a) Rocker Arms:

Rocker arms are produced using a shell mould, stack moulding method. Thin wall castings with good dimensional accuracy and low moulding cost are produced by this casting process. The castings are heat treated to break down any residual carbide and to fully ferritize the matrix, thus providing maximum casting ductility. A key feature of the application of rocker arm is utilization of the ability of ferritic ductile iron to be coined to final dimension, thus minimizing costly machining operations. Following these operations, rocker arms are batch austenized, oil quenched and tempered to provide the strength and wear resistance required for the final engine application.

(Figure: 3.71a: Rocker Arm)

(http://dir.indiamart.com/impcat/rocker-arms.html) dt.19/03/2015

A rocker arm is a valve train component in internal combustion engines. Rocker arm acts on by a camshaft lope and typically in between the pushrod and the intake and exhaust valve. This activity helps to allow fuel and air to be drawn in to the combustion chamber during the intake stroke or exhaust gases to be expelled during the exhaust stroke [89].

(b) Rear Axle Components:

Rear axle carriers, gear cases and gear case covers are typical examples of as-cast ferritic ductile iron casting applications. Requirements for these types of components are good ductility, strength and shock resistance as well as excellent machinability. The rear axle assembly is used in rear-wheel drive vehicles. This assembly is the final leg of the drive train. It is often called the final drive or rear end. The rear axle assembly is often mistakenly called the differential. The differential is only part of rear axle assembly. The differential investigation is carried out for vertical press force, opening of housing in lateral direction, shims adjustment from rear without force and release of press force [90].

(Figure: 3.71b: Rear Axle Components)

(http://www.4wd.com/hardparts/HPDiagramList.aspx?HPCatID=7) dt.19/03/2015

(c) Crankshafts:

A crankshaft is a real mechanical part. It is able to perform a conversion between reciprocating motion and rotational motion. In a reciprocating engine, it translates reciprocating motion of the piston into rotational motion and in a reciprocating compressor; it converts the rotational motion into reciprocating motion. During renaissance, the first depictions of the compound crank in the carpenters brace appear between 1420 to 1430 A.D.in various northern European artwork and subsequently it was adopted. The automotive crankshaft is considered the “old reliable” ductile iron component. The first conversions from cast steel to ductile iron crankshafts began in 1951. The excellent field performance of the millions of ductile iron crankshafts used in automotive, truck, and tractor service is mainly due to the outstanding mechanical properties and quality of pearlitic ductile iron castings. While steel forgings are still used for special engine applications, with today’s ductile iron technology most of the remaining forged steel crankshafts can be successfully converted into ductile iron [91].

(Fig. 3.71c: Crankshaft)

(http://www.maxspeedingrods.co.uk/high-performance-ford-cosworth-bda-bd-82mm-stroke-4340-en24-steel-billet-crankshaft.html) dt.20/03/2015

(d) Ring and Pinion Gears:

Prototype ring and pinion gears castings are shown in fig.3.67d. Gearing represents major potential new applications which are for ductile iron. Ductile iron gearing can be cast as a toothed blank, significantly reducing the amount of material to be removed during machining. Compared with current forged steel practice, ductile iron offers the potential for major reduction in machining costs for components such as those shown. It allows both axles to turn at the same speed when the vehicle is moving in a straight line. The drive axle assembly directs drive line torque to the vehicles drive wheels. The gear ratio of the drive axle's ring and pinion gear is used to increase torque. The differential serves to establish a state of balance between the drive wheels and allows the drive wheels to turn at different speeds when the vehicle changes direction [75].

(Fig.3.71d: Prototype ductile iron Ring and Pinion gear)

(http://3.imimg.com/data3/TE/DR/MY-3100927/pinion-gear-250x250.jpg) dt.20/03/2015

(e) Follower Arms:

Ductile iron was selected for these applications as a result of its excellent fatigue strength. In addition, ductile iron is far more readily machinable than hardenable iron. It provides wear resistance for a server service application. The follower arm sits on a stud near one end and contacts the valve near the far end of its length. The camshaft rotates against a pad on the follower arm surface to control valve opening. The camshaft lobes are hardenable iron with a hardness of Rc 50 - Rc 60. The follower arms require good machinability and excellent fatigue strength and wear resistance [75].

(Fig.3.71e: Ductile iron follower arm)

(http://newsletter.1aauto.com/articles/control_arms/iron_control_arm.jpg) dt.20/03/2015

3.72 Pressure Pipes and Fittings

Ductile iron pipe has been used to transport water and other liquids, which testifies the ball better than gray cast iron pipe. The excellent physical characteristics of ductile iron make the pipe line withstand the high operating pressure and can withstand the excavation near pipelines and municipal construction and satisfy transportation requirements. The first ductile iron pipe was apparently cast by Luncburg Foundry in 1948. During the late 50s and early 60s great effort was expanded in learning new melting and casting techniques needed for ductile iron pipe production. Ductile iron pipe has a greater acceptance for use in gravity mains and interceptors as it is being used as a standard material for sewer force mains, pump station piping and waste water treatment plant mechanical piping. Ductile iron pipe is designed and manufactured in accordance with published standards of the American National Standards Institute (ANSI), the American Water Works Association (AWWA) and the American Society of Testing and Materials (ASTM). Most ductile iron sewer installations laid in accordance with good engineering practice should for a minimum of 50years with a goal of 100 years [92].

The main advantages of ductile iron pipes are:

- High working pressure compared to other types of pipes
- High tensile strength, good elastic modulus and excellent ductility, making it suitable for high stress applications and where pressure surge may be experienced.
- High corrosion resistance
- Excellent hydraulic flow
- Ease of installation

- Long life time
- Can accommodate ground movement

Main applications of ductile iron pipes are:

- Drinking and irrigation water networks
- Sewerage networks
- Fire fighting systems

The history of ductile iron pipe usage in the field has been a remarkable one with virtually no field failures. The obvious superiority of ductile iron over gray iron as an engineering material comes into play in the design of ductile iron pipe.

3.73 Agriculture, road and construction applications

Modern agriculture requires a reliable and long service life of agricultural machinery. The entire agricultural industry is widely using ductile iron castings including tractor parts, ploughs, brackets, clamps and pulleys. For other types of agricultural machinery including bulldozers, moved into machines, cranes and compressors, ductile iron castings have a very wide range of applications. The service lives of agricultural machine parts of the soil cultivation are generally affected by abrasive wear because of ploughing conditions. In order to avoid such problems, ADI is used for manufacturing of such machinery parts. An appropriate combination of chemical composition and heat treatment can yield in ductile irons an optimum combination of strength, toughness and wear resistance for different ploughing conditions [93].

3.74 Wind Energy Applications

As the standard of living increases worldwide, one major consequence is an increase in the demand for electrical energy in the residential, as well as commercial sectors. Therefore alternative energy sources, particularly renewable energy have become a source of great interest around the world. Wind power is a renewable, predictable and clean source of energy. It is observed that wind energy will capture most of the installation up to 2020. Ductile Iron is being used as the right material for manufacturing of many wind mill parts. The major advantages over steel being higher castability, lower density, improved machinability, design flexibility, while offering the required mechanical properties. Although some pearlitic and ADI castings are used for certain parts (e.g. gears), most of the Ductile Iron components found in wind energy turbines satisfy the stringent ENG-GJS-400-18-LT specification. In a global world always requiring more energy but becoming highly conscious about the environment and the effect of human activities on it, renewable sources of energy have become an unavoidable choice for industrial countries, and amongst these renewable sources of energy, wind energy has gained general acceptance. Although most of the wind turbine suppliers are European, the development of the North American wind energy market makes local sourcing of the Ductile Iron components unavoidable. The North American Ductile Iron foundries can produce the high quality level required for these castings and should have a close look to the opportunities that are now opened to them. The wind power industry has been growing astonishingly in recent years. It is expected that the present wind power share of about 1% of global power consumption will grow to at least 10% by 2020 [94-95].

(Fig 3.74a)

(Fig 3.74b)

Figure 3.74a: Ductile iron rotor hub for a V52-2 Turbine

(http://www.sorelmetal.com/en/publi/PDF/110_EN.pdf) dt.22/03/2015)

Figure 3.74b: Bearing Housing for wind turbine equipments

(http://www.indiamart.com/js-auto-cast-foundry/wind-turbine.html)

dt.20/03/2015

Chapter 4

4. Material Preparation & Experimental Procedures

This chapter describes the material preparation and experimental procedures or the processing and characterisation of thick wall ductile iron castings in as-cast conditions. It presents the detail characterization of graphite morphology, tensile properties, and effect of processing variables on the mechanical properties as well as alloying elements. During the present investigation, an attempt was made to correlate the results obtained by the addition of copper and nickel in different specimens during its production. Samples for this investigation consisted of tensile test bars having with and without the addition of alloying elements. This chapter introduces the experimental procedures utilized to characterize the thick-walled (≥ 20 mm) ductile iron castings. Different experiments were conducted for studying the effect of alloying elements, processing variables, materials used on the spheroidal graphite iron castings in as-cast conditions. The composition and processing of the material and various experimental techniques used to determine different properties of the material have been discussed in this chapter.

4.1 Materials

Ductile iron was produced by using Pig iron, steel scraps, coconut charcoal and SG iron returns. Ferro alloys were added to meet the desired composition. The melting was carried out in a coreless medium frequency induction foundry furnace. The following raw materials were used for the production of thick-walled ductile iron castings. The chemistry of all the raw materials used is obtained from manufacture's analysis.

A. Pig iron

The quantity of pig iron as per charge mix was used for the production of ductile iron castings. The composition of the pig iron is given in table 4.1a.

Table 4.1a Chemical composition of the pig iron in wt%

C	Si	Mn	S	P	Fe
4.12	1.72	0.142	0.025	0.062	Balance

B. Steel Scrap

Steel scrap as per required quantity was used in the production of thick-walled ductile iron castings. The composition is given in table 4.1b.

Table 4.1b Chemical composition of the steel scrap in wt%

C	Si	Mn	S	P	Fe
0.037	0.033	0.128	0.005	0.016	Balance

C. Ferro-Silicon-Magnesium (size 15-25 mm)

Treatment of the molten metal was carried with ferro-silicon-magnesium for spheroidization. This process is known as inoculation. The composition of Fe-Si-Mg is mentioned in table 4.1c.

Table 4.1c Chemical composition of Fe-Si-Mg in wt%

Si	Mg	Ca	Al	Fe
45.32	5.72	1.10	0.93	Balance

D. SG Iron Return (foundry returns like risers gates etc.)

SG iron return was charged in the furnace during as per required quantity for the production of ductile iron castings. The composition is mentioned in table 4.1d.

Table 4.1d Chemical composition of SG iron Return in wt%

C	Si	Mn	S	P	Cr	Ni	Cu	Mg	Fe
3.52	2.06	0.16	0.010	0.022	0.015	0.018	0.014	0.048	Balance

E. Ferro-Silicon Inoculants (Fe-Si, size 2-6 mm)

This material was used as post-inoculants during ductile iron production. Nodule count usually increases with the increase in inoculation. This process was carried out just before pouring as per standard foundry practices to get better result. It is also known as in-stream and in-mould inoculation practice. The composition of the material is given in table 4.1e

Table 4.1e Chemical composition of Fe-Si inoculants in wt%

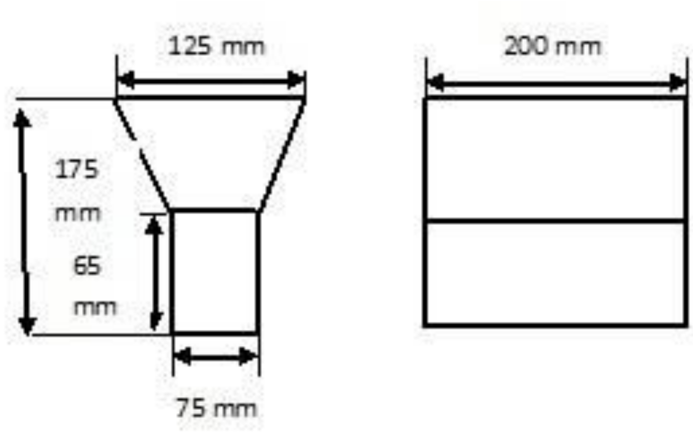
Si	Al	S	P	Ca	Ba
74.21	1.08	0.004	0.032	0.17	1.98

4.2 Experimental Procedures

The following methods were adopted for preparation and characterization of ductile iron castings. The specimens were made for tensile properties as per EN1563 standard. All the tests were performed at room temperature except impact test. It was carried out at -20^0C. Different instruments were used for analyzing the test specimens.

4.21 Melting and Casting

The melt history, including the type of charge material, chemistry and molten metal processing of a cast iron melt has a pronounced effect on the final structure and properties of the castings poured. For this study, fifteen melts of ductile irons were produced using open ladle treatment method. The charge mix consisting of 100 kg pig iron, 290 kg steel scrap, 110 kg SG iron returns and 20 kg coconut charcoal (C=55 wt % as per manufacturer's analysis) was melted in a coreless medium frequency induction furnace having a capacity of 1000Kg. Simultaneously, a ladle was preheated to 850-900^oC and Fe-Si-Mg alloy was kept at the bottom of the ladle and was covered by steel scrap. The open surface of the ladle was covered with tundish. The molten metal was tapped in to the laddle. The tapping temperature of the molten metal was 1480^oC . After tapping, commercial argon gas was punched through the steel pipe to the molten metal for proper mixing and initiation of spheroidization process followed by addition of 1% Fe-Si inoculants. At this time, the sample was taken from the molten metal for final chemical analysis. The treated iron was poured into furan resign sand moulds (Y block specimen as shown in fig 4.21as per ASTM A536-84 standard) bonded with epoxy resin and catalyst. The time interval from tapping to pouring was maintained from 4 to 5minutes. The pouring temperature was 1370^oC. A total of fifteen melts of ductile iron was produced by the similar process with proper post-inoculation and varying chemical composition by addition of nickel and copper with required quantity. The basic melting processes are furnace operation including charging, melting, composition analysis, composition adjustment, slag removal and superheating up to 1510°C.



(Fig 4.21 Schematic drawing of 'Y' block casting)

4.22 Spheroidizing Treatment

This is the critical step in the production of ductile iron castings. The amount of residual magnesium present in the melt during solidification ranges from 0.03 to 0.05 wt%. Magnesium content less than this amount in the melt results in flake graphite and more than this amount results in exploded graphite. In both the cases, it contributes to lowering of ductility of the cast iron. Magnesium, in addition with some rare earth elements, is commonly used for this process. The magnesium in the form of Fe-Si-Mg violently reacts with liquid iron and effectively cleans the melt of excess oxides and combines with sulphur to form MgS, which acts as a nucleation site for graphite nodules. It helps to change the surface energy of the graphite and allows precipitation in the form of spheroids.

The sandwich method was employed for spheroidizing process. The calculated amount of Fe-Si-Mg is kept on the bottom of the ladle and covered with steel cheeps. The opening face of the preheated ladle is covered with tundish. The tapping time of the metal is around 35 to 40 seconds and the temperature loss during magnesium treatment is around 40 to 50^0C. After magnesium treatment, the liquid metal is poured in the mould within a very short period of time.

4.23 Inoculation

Fe-Si is used as inoculants for the manufacturing of ductile iron castings. Immediately after the magnesium treatment, the metal is inoculated. The effect of inoculants starts to fade from the time it is added. Significant fading occurs within five minutes of inoculation. Inoculation process has multiplying effects on the formation of nuclei and solidifying cells in ductile iron for its production. Three types of inoculation technique have been deployed for this study in order to get quality ductile iron castings for heavy section size. The three techniques are pre-inoculation, post-inoculation and late-inoculation. The summery is given below.

Pre-Inoculation

In this step, Fe-Si of desired size is added to the stream of the iron filling the treatment ladle. This FeSi in combination with Mg contributes to weaken the carbide promoting effect of Mg and adjust the silicon content in the iron. The primary function the inoculants are to add nucleation sites to facilitate the growth of graphite particles versus the growth of carbides.

Post-Inoculation

This is the most important practice of inoculation technique. This process is carried out during commercial grade argon purging in the ladle. It helps to restore the nucleation potential of the iron and to offset the carbide promoting effect of magnesium.

Late-Inoculation

In this step, the inoculants are added in the metal stream during filling the mould. It is also most effective step in the inoculation series. This process is carried out to ensure the high nodule count and to minimize intercellular defects detrimental to mechanical properties.

4.24 Preparation of furan resin sand

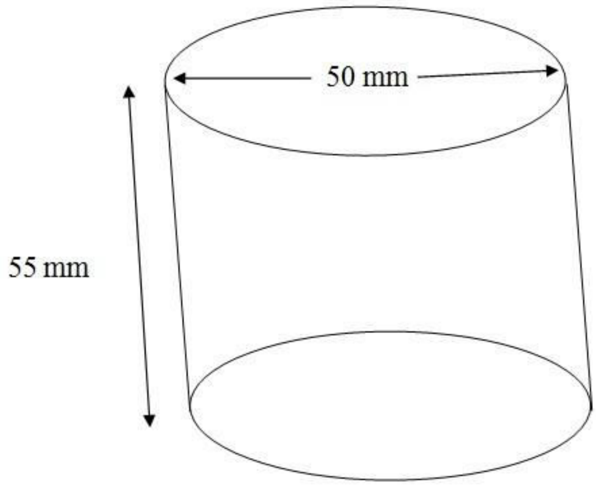
The furan resin sand was used in mould preparation in which the molten metal was poured. In order to get better quality casting , the role of furan resin sand is of great importance. The physical parameters like binding strength, compresive strength, permeability has a remarkable effect on the property enhancement of ductile iron. The furan resin sand was prepared by self setting furan binder system as per standard foundry practices. It was prepared in a mixture (Make: Impianti Macchine Fonderia, italy) by taking 1.2% epoxy resin, 45% catalyst, 60% reclaimed sand and 40% fresh silica sand. The foundry grade resin used was urea formaldehyde/furfural alcohol and the catalyst used was paratoulene sulphuric acid. They are hardened by polymerization at room temperature under the influence of acid catalyst. The sieve analysis of fresh and reclaimed sand, physical parameters analysis of furan resin sand was carried out by sand testing equipments (as per ISS 460 standard). The scematic diagram of furan resin sand specimen used for testing was shown in fig 4.24a and the sand testing equipments are shown in fig 4.24b. The results of both fresh sand and reclaimed sand was given in table 4.24a and the results of the furan resin sand is listed in table 4.24b

Table 4.24a Results of fresh and reclaimed sand

Sand	Moisture (%)	Clay (%)	GFN (%)	GD (%)	Density (gm/cc)	LOI (%)	ADV (%)	Sulphur (%)
Fresh	0.04	0.16	42.22	80.92	1.44	0.28	0.45	0.038
Reclaimed	0.10	0.36	43.76	86.12	1.50	4.60	2.54	0.060

Table 4.24b Results of Furan Resin Sand

Physical parameter	**Values**	**UOM**	**Testing Time**
Dry Permeability	> 500	mm head of water	Just after the sample preparation
Dry Compressive Strength	34	Kg/cm^2	After 4 hours of sample preparation
	42	Kg/cm^2	After 8 hours of sample preparation
	50	Kg/cm^2	After 24 hours of sample preparation

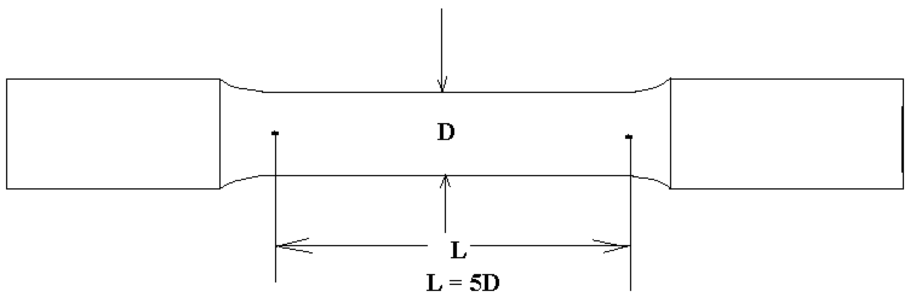


(Fig 4.24a Schematic diagram of furan resin sand specimen)

(Fig 4.24b Sand Testing Equipments)

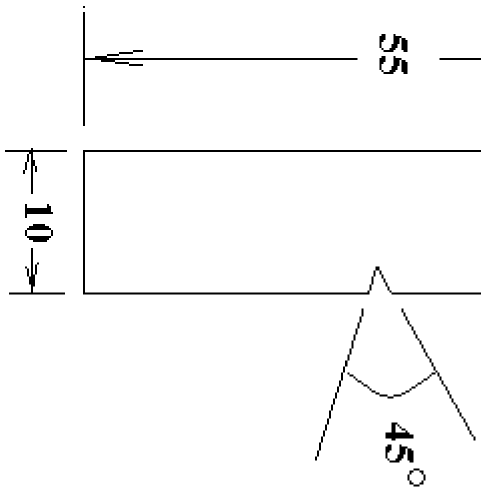
4.25 Tensile and Impact Testing

The tensile testing specimens are prepared from the casting obtained from the ‘Y’ block casting. The tensile strength, yield strength and elongation are determined using digital Universal Testing Machine (UTM) as per EN1563 specification. Fig.4.25a shows the round tensile test specimen. Charpy impact test at -20^{o}C in a Shimadru Pendulum (Fig 4.25d) of 300J maximum capacity (Least count 0.5 joule) was performed with V-notched specimen (Fig. 4.25b, as per BSEN 10045-2-1993 standard). Before performing the Charpy impact test, the specimens are cooled for 5 minutes in a bath containing methanol and dry ice for temperature down to -20^{o}C. The mean impact values are calculated taking average results of three specimens.Fig.4.25c shows UTM. The schematic diagrams of the specimens are as shown below.



(Fig. 4.25a Schematic diagram of round tensile test specimen)

Where, D = Gauge diameter = 14 mm, L = Gauge Length = 5x14 = 70 mm



(Fig.4.25b V-notched Charpy impact test specimen, dimensions are in mm)

(Fig. 4.25c Digital Universal Testing Machine)

Salient Features of Digital Universal Testing Machine (UTM):

- Model- UTE 100
- Maximum Capacity 100MT
- Make Fuel Instruments & Enginner's Pvt Ltd, Maharastra, India
- Rupture (% peak) 50
- Preload (% full scale) 0.05
- Safe Load (kN) 900
- Hold time (sec) 10
- Load rate (kN/min) 65
- Stress rate (kN/Sq.mm/min) 10
- Elongation rate (mm/min) 2
- Strain rate (% strain/min) 1
- Initial valve open (10-99%) 25

(Fig. 4.25d Impact test machine, Make FIE, Model IT30)

The hardness of the ductile iron is measured in BHN scale. A load of 3000 Kg is applied on each specimen for the analysis. The instrument used for carrying out the measurement is shown in fig 4.25e and fig 4.25f as follows. Five readings were taken for each specimen and the average value has been reported.

(Fig. 4.25e Brinell and Rockwell Hardness Tester, Make: FIE)

(Fig. 4.25f Equotip hardness testing machine, Make: Proceq SA, Switzerland)

4.26 Metallographic Examination

It always remains the most important tool for the study of microconstituents of any material. For microstructural investigation, the following microscope and image analyzer were used.

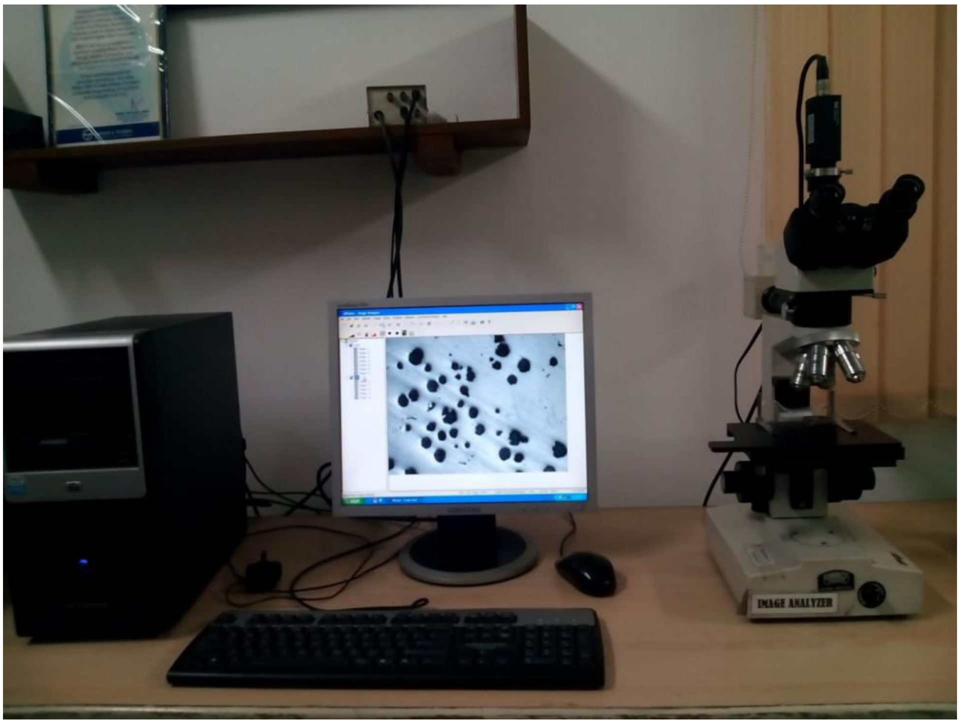
Optical Microscope:

The samples for metallographic anlysis were prepared by using standard techniques. The samples were taken from the centre of the castings and were mounted with Bakelite. The surfaces of the samples were ground on SiC paper from 220 to 900 grit (emery sheets) followed by disc polishing using 1µm cloth coated with diamond paste to reveal the microstructure. The polished samples were etched with 2% nital (2% concentrated nitric acid and 98 ml methanol). The etched specimen microstructure was analyzed and then photograph was taken with high resolution digital camera with various magnifications. Fig.4.26a shows the optical microscope used for this investigation.

(Fig 4.26a Optical Microscope, Make: Union Tokyo, Model: RMM 3314)

Image Analyzer:

The mounted samples aftermetallographic examinations were kept under Image Analyzer (Fig 4.26b) to study the nodule counts, nodularity, graphite morphology and matrix characterization.



(Fig 4.26b Imaze Analyzer, Make: Metal Power, Model: 210)

4.27 Composition Analysis

The final composition of all the specimens of fifteen melts were analyzed using a spectrometer. Standard coin samples were prepared for the spectrometric analysis. All the fifteen heats/melts were numbered as from S1 to S5, N1 to N5 and C1 to C5 as per the composition for better identification. The composition of all melts were mentioned in the respective results and discussion chapter. Fig. 4.27 shows the spectrometer used for the analysis of the melts for the study. The main features of the spectrometer is its analysis frequency. It takes 30 seconds for analyzing the chemistry of the melt and gives accurate percentage of 24 elements present in the melt. The Instrument used for chemical analysis is “Spectro-Analytical Instrument, model M9.” Types of materials like low alloy steel, medium alloy steel, High alloy steel (stainless steel), SG iron, cast iron, Ni-Hard IV, Hi-chrome iron and manganese steel are also analysed by this spectrometer. The operational principle of the instrument is Atomic Emission Run with continuous AC supply followed by XL grade (99.99% purity) argon gas.

(Fig. 4.27 Spectrometer, Model-M9, Sectro Analytical instrument, Jerman)

Chapter 5

5. Results & Discussion

With the development of automotive, cast pipe, windmill, heavy machine manufacturing and nuclear power industry, the applications of spheroidal graphite iron are continuously expanding. Around 80% of the ductile iron castings components are used in automotive applications which are manufactured in as-cast condition [96]. The as-cast ductile iron posses many advantages viz., energy saving, equipment investment decreasing, production cycles shortening, production cost reducing and promoting of competitiveness. Since, the as-cast ductile iron casting components are being used in many engineering applications; these applications include exposure to various temperatures [62]. During the last decades, the as-cast ductile iron production is continuously increasing. This fact is mainly due to the improvement in casting technology and metallurgical advances favouring enhancement in mechanical properties. Since, the mechanical properties are strictly related to the matrix structure and graphite morphology, one should have a control on microstructure of as-cast ductile iron by controlling the process parameters [26, 72].

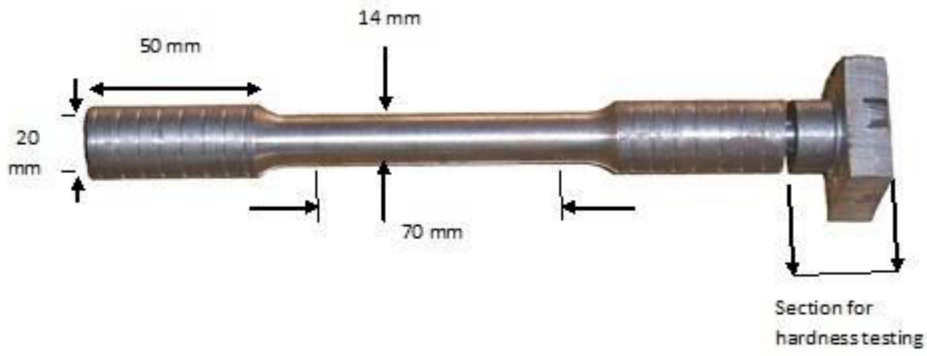
The present investigation puts emphasis on the production of heavy section (thick-wall, ≥20 mm) as-cast ferrite ductile iron castings and enhancement of mechanical properties by controlling the process parameters. The alloying elements (Nickel and copper) were added in the melt (Chapter-4) and its effect on the mechanical properties and matrix structure were studied. Fifteen melts were produced as per standard foundry procedures. The sample identification for all the melts (five melts without copper and nickel, five melts with nickel and 5 melts with copper) are mentioned in chapter-4. The tensile properties were determined as per EN1563 specification. The correlation between tensile properties, impact toughness, hardness and microstructure was investigated. The manufacture and process control was also studied. The results and discussion of the present investigation is summarized here.

5.1 Effect on mechanical properties & matrix structure without the addition of Nickel and Copper

Five melts of as-cast spheroidal graphite iron castings were produced without the addition of nickel and copper. All the melts were properly processed to get defect free quality castings. After melting and casting followed by successful process control, the metal was poured into furan resin sand moulds to obtain Y-shaped 75 mm blocks. All the samples were machined for tensile test (Fig 5.1a). Identification mark was given to all individual casting (S1 to S5). Table 5.1a illustrates the melt chemistry of the castings.

Table 5.1a Melt chemistry in wt% (melt no. S1 to S5)
[Specimens having very little amount of Cu and Ni]

Melt No.	C	Si	Mn	S	P	Cr	Ni	Mo	Cu	Mg	CE
S1	3.51	2.04	0.150	0.007	0.024	0.018	0.022	0.002	0.023	0.045	4.19
S2	3.54	2.08	0.158	0.008	0.026	0.020	0.021	0.003	0.024	0.048	4.23
S3	3.58	2.14	0.160	0.009	0.025	0.017	0.018	0.004	0.028	0.046	4.29
S4	3.62	2.20	0.164	0.010	0.024	0.019	0.019	0.003	0.025	0.048	4.35
S5	3.66	2.28	0.174	0.009	0.025	0.020	0.020	0.004	0.022	0.047	4.42



(Fig 5.1a Tensile Test Specimen)

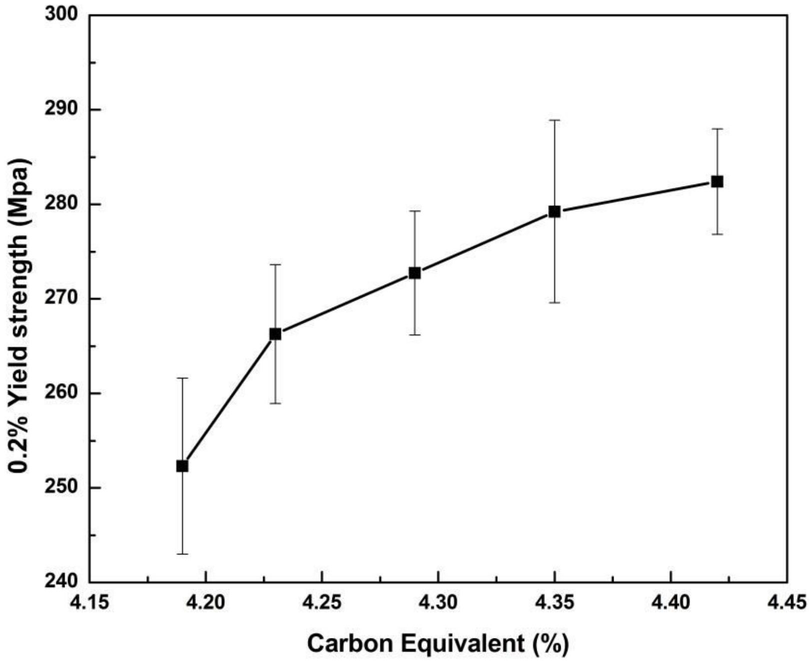
The mechanical properties viz., tensile strength, yield strength, elongation, impact strength and hardness were determined from the specimens and the results are tabulated in table 5.1b.

Table 5.1b Mechanical properties (melt no S1 to S5)

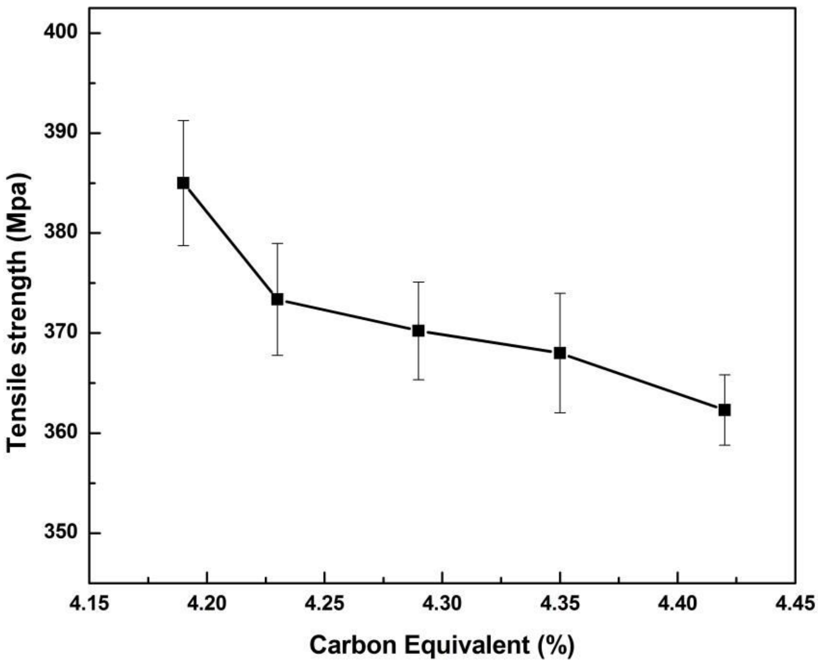
Melt No.	**0.2% YS (Mpa)**	**UTS (Mpa)**	**EL (%)**	**Impact (J)(at -20^{0}C)**	**Hardness (BHN)**
S1	252.30	385.00	17.50	9.00	138
S2	266.27	373.38	18.20	10.67	134
S3	272.72	370.22	19.10	11.67	132
S4	279.22	368.00	19.50	12.00	130
S5	282.40	362.32	20.20	12.50	126

5.11 Effect of Carbon Equivalent on Mechanical properties

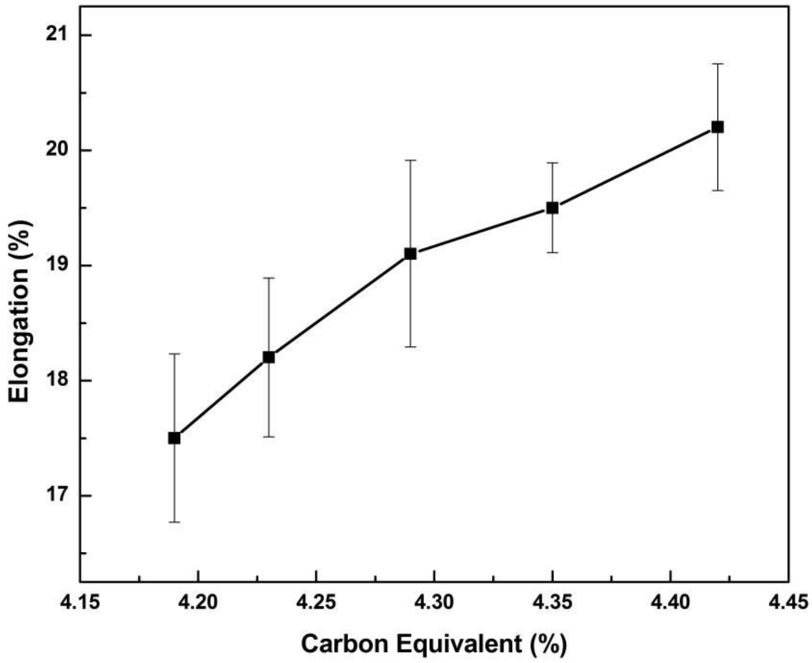
The effect of carbon equivalent (CE) on 0.2% offset yield strength, tensile strength, Elongation, V-notched charpy impact (at -20^{o}C) and hardness is shown in fig 5.11a, 5.11b, 5.11c, 5.11d and 5.11e respectively.



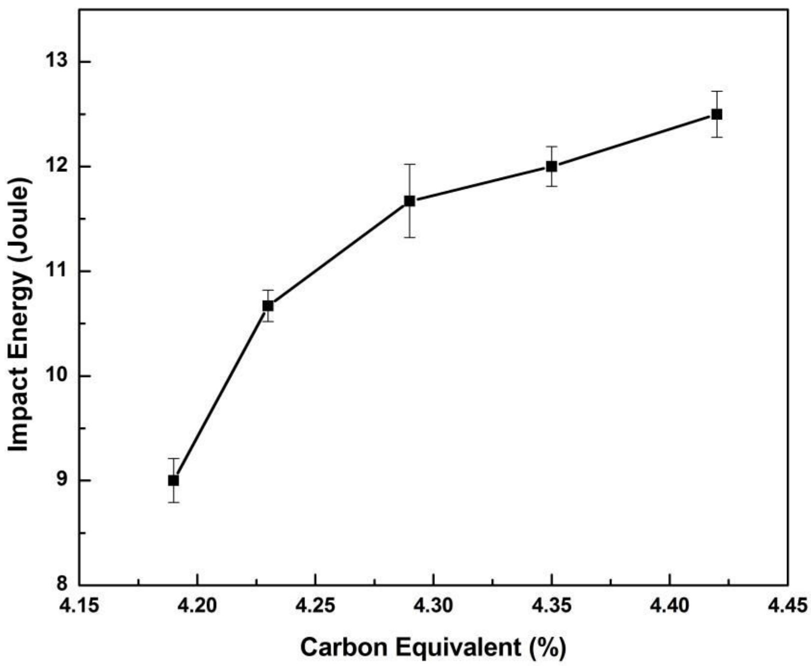
(Fig. 5.11a Effect of CE on 0.2% YS)



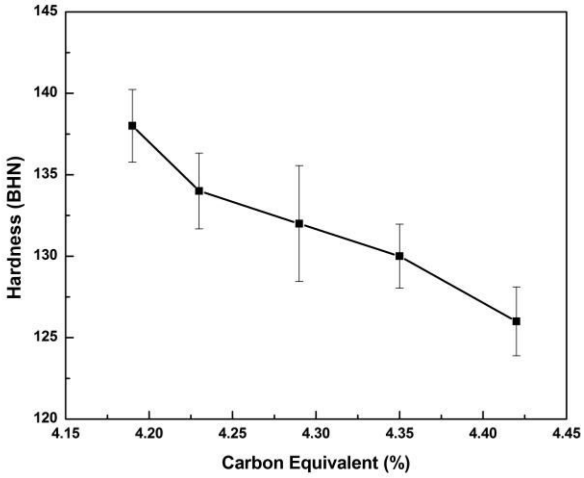
(Fig. 5.11b Effect of CE on Tensile strength)



(Fig. 5.11c Effect of CE on Elongation)



(Fig. 5.11d Effect of CE on Impact Strength)



(Fig. 5.11e Effect of CE on Hardness)

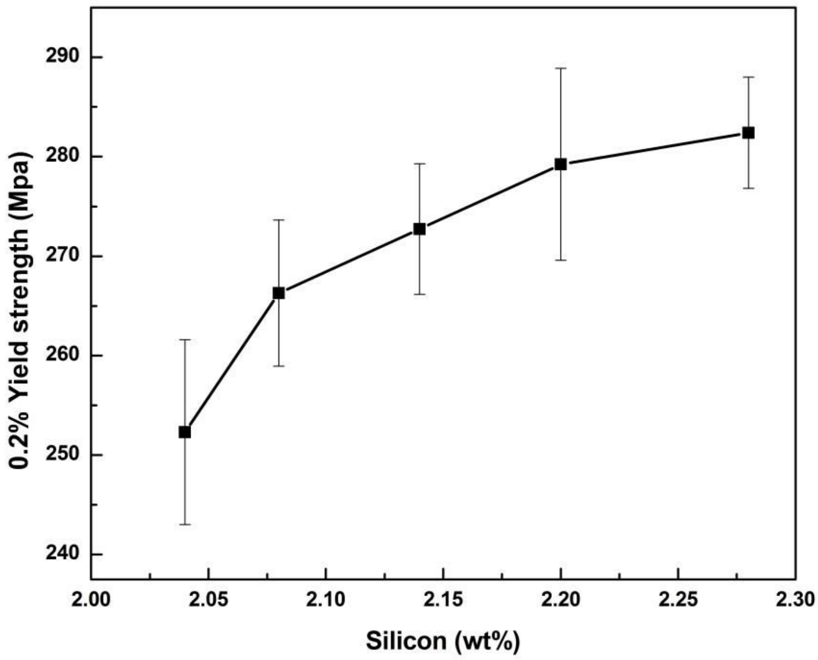
(Fig. 5.1c Microstructure showing chunky graphites, 100 X, source: self research work)

The result shows that the yield strength (Fig.5.11a) increases significantly with the increase in CE whereas tensile strength (Fig. 5.11b) decreases. Other parameters like elongation (Fig. 5.11c), Impact strength (Fig.5.11d) increases and hardness (Fig.5.11e) decreases with increase in CE as a result of ferrite content in the metallic matrix. The literature indicates that the eutectic composition of ductile iron has a carbon equivalent equal to 4.3. However, most of the commercial foundry maintaining the CE ranges from 4.2 to 4.5. For melts more with higher CE, the graphite nodules are more compact and less irregular in shape. However, the higher CE irons also have a higher likelihood of exhibiting carbon floatation i.e., the graphite nodules grow enough to float to the top of the melt. It is also known that chunky graphite (melt no. S4 and S5) is more prevalent in irons with a CE greater than 4.3 [97, 98].

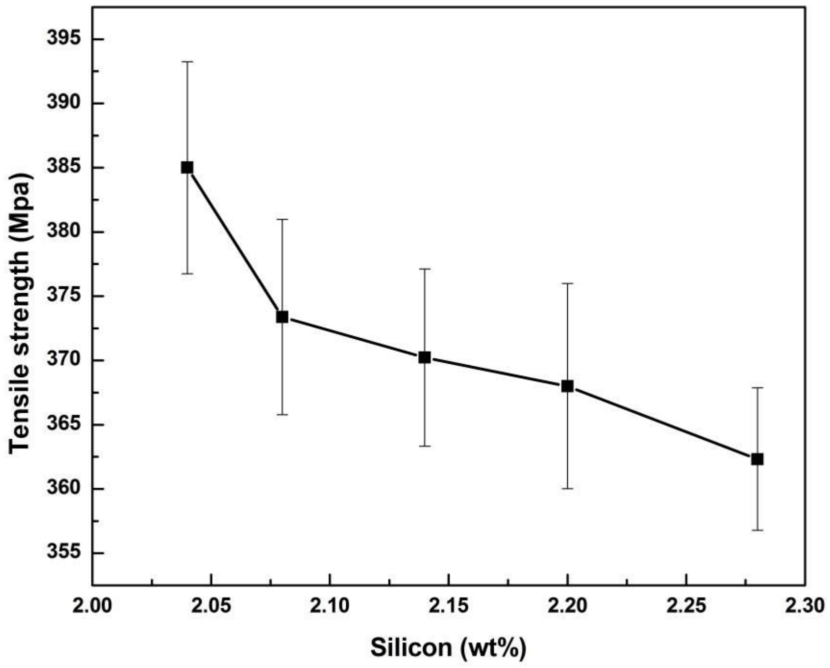
For getting sufficient nodule count, the CE is maintained close to eutectic composition (melt no. S1, S2 and S3) or slighter higher as graphite nucleation and growth occurs in eutectic and hypereutectic ductile irons. In hypereutectic iron, graphite nodules nucleate first and grow in the liquid and depleting it of carbon until the concentration reaches the eutectic composition. The decrease in tensile strength (fig.5.11b) is directly related to the effect of CE on degeneration of graphite (fig. 5.1c). The CE plays an important role for the formation of chunky graphite in the melt during solidification of thick-walled/heavy section ductile iron castings in as-cast condition which creates adverse effects on the mechanical properties. The large sections of these castings lead to very slow solidification resulting in the formation of degenerated graphite [99, 100].

5.12 Effect of Silicon on Mechanical Properties

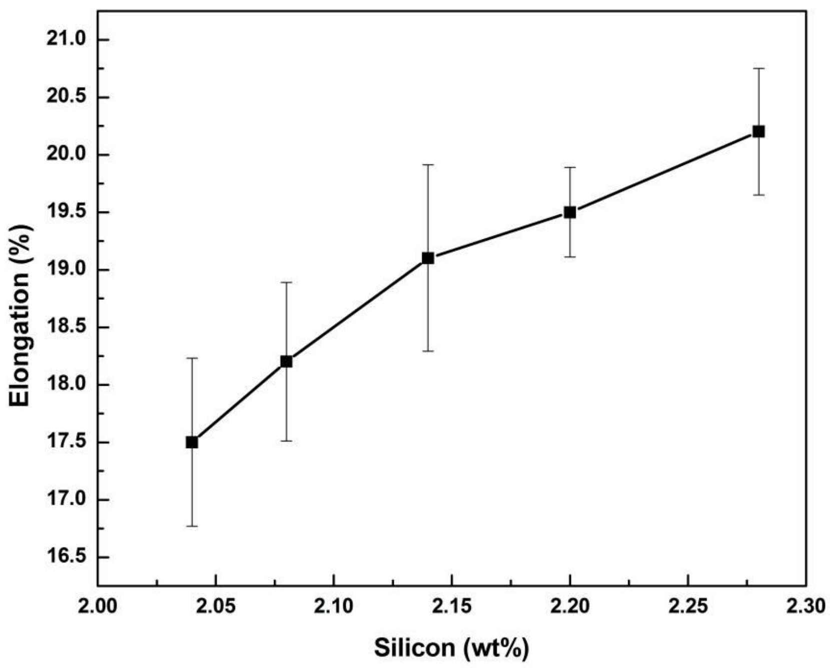
The influence of silicon on 0.2% offset yield strength, tensile strength, Elongation, V-notched charpy impact (at -20^{o}C) and hardness was studied for the melt no. S1 to S5 and the result is shown in fig 5.12a, 5.12b, 5.12c, 5.12d and 5.12e respectively.



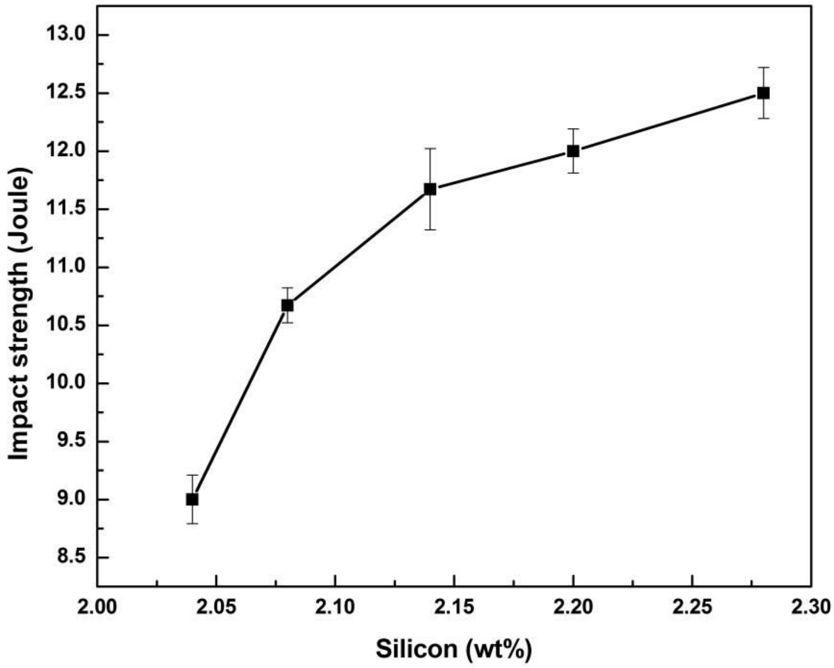
(Fig 5.12a Effect if Silicon on 0.2% Yield Strength)



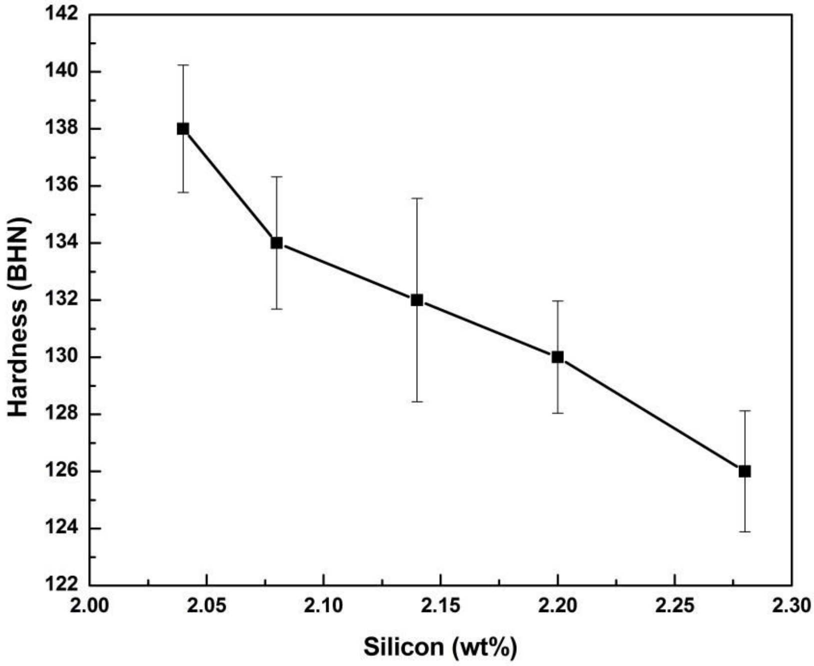
(Fig. 5.12b Effect of Silicon on Tensile strength)



(Fig. 5.12c Effect of Silicon on Elongation)



(Fig. 5.12d Effect of Silicon on Impact Strength)



(Fig. 5.12e Effect of Silicon on Hardness)

The change in properties of as-cast ductile iron as a function of increasing amount of silicon was studied in this investigation. Silicon shows the most significant effect on the mechanical properties. The decrease in tensile strength (fig. 5.12b) results from the increase in ferrite content in the matrix. The microstructure of the ductile cast iron can be changed from fully carbidic (through pearlitic) to fully ferritic merely by changing the amount of silicon. The increase in Silicon content (melt no. S1 to S5), decreases the quantity of pearlite in the metallic matrix and at the same time it acts as a potent ferrite strengthener and graphitizer. The overall change in the properties depends on the two effects viz., decrease in pearlite content and ferrite strengthening effect of silicon. The decrease in strength (fig. 5.12b) and hardness (fig. 5.12e) is due to the decrease in amount of pearlite and the increase in strength of already existing and newly formed ferrite by solid solution strengthening. The decrease in strength properties and increase in ductility (fig. 5.12c) is in accordance with the relative proportions of the matrix constituents [96]. Since silicon is a strong ferrite promoter and graphitizer, at high levels (more than 2.8 wt% Si), it is generally considered to be the detrimental especially with respect to the ductile to brittle transition temperature (DBTT) and the brittleness of ductile iron will significantly increase when Si content extends to a certain extent. It is well known that the transition temperature of materials is appreciably influenced by microstructure and it increases as the pearlite to ferrite ratio increases. Even though silicon acts as a stress raiser, at the same time it has a pronounced effect on the pearlite to ferrite ratio. This may be partially responsible for the improved impact results (fig. 5.12d) obtained. Further addition of silicon for obtaining 100 percent ferritic structure may exert its full stress raising effect with a drastic increase in transition temperature. Hence the silicon content is controlled for the production of thick-walled as-cast ductile iron castings [101].

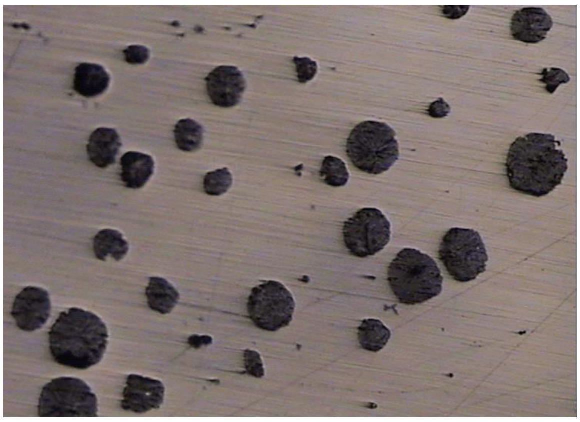
The decomposition of austenite to ferrite plus graphite or to pearlite in spheroidal graphite cast iron depend on many factors among which basic compositional changes (addition of alloying elements viz., Si, Mn, Cu etc.) plays a vital role on influencing the properties of SG iron. Especially in heavy section castings, the control on microstructure is of practical importance as the use of alloying elements promoting or inhibiting the ferrite or pearlite reactions is an important factor [102].

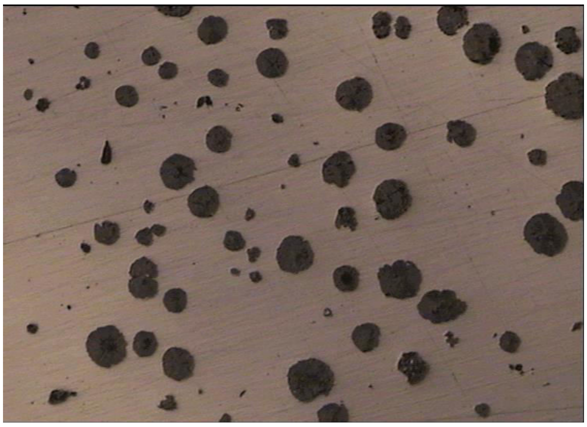
5.13 Microstructural Characterization (Melt No. S1 to S5)

The microstructural analysis was carried out with the help of the digital image analyzer for the melt nos. S1 to S5. The results are illustrated in table 5.13 and the microstructures are shown in fig. 5.13a, 5.13b, 5.13c, 5.13d and 5.13e respectively for the melt nos. S1 to S5.

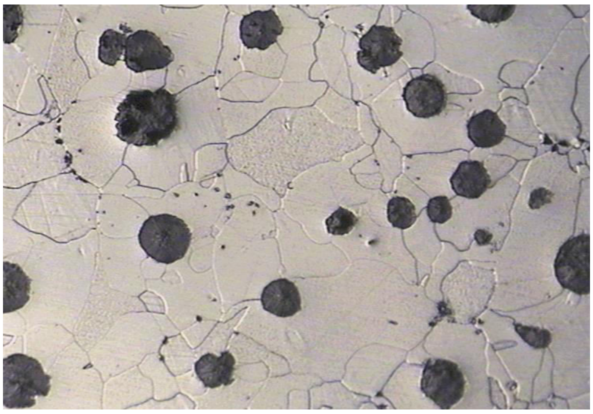
Table 5.13 Microstructure description (Melt no. S1 to S5)

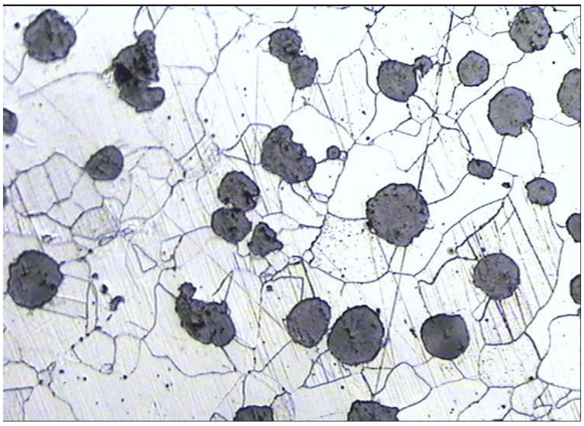
Melt No.	**Matrix**	**Nodularity (%)**	**Nodule Count (Nos/mm^2)**
S1	90% ferrite, 10% pearlite	70	123
S2	94% ferrite, 6% pearlite	74	127
S3	96% ferrite, 4% pearlite	78	134
S4	97% ferrite, 3% pearlite	80	159
S5	98% ferrite, 2% pearlite	85	178



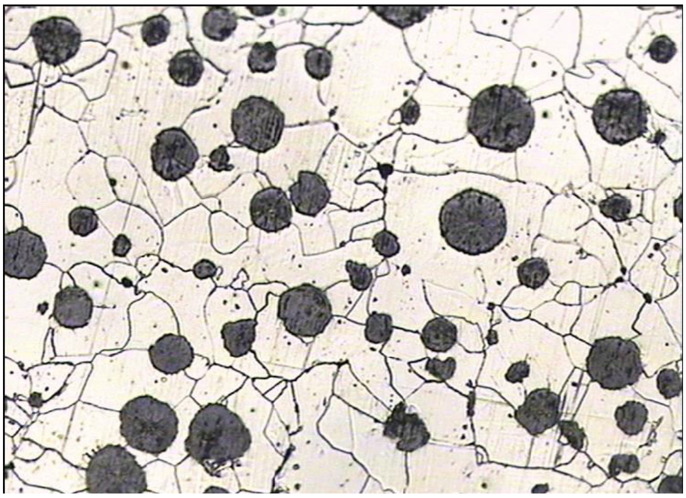


(Fig. 5.13a Microstructure of melt S1, 100X) (Fig. 5.13b Microstructure of melt S2, 100X)





(Fig. 5.13c Microstructure of melt S3, 100X) (Fig. 5.13d Microstructure of melt S4, 100X)

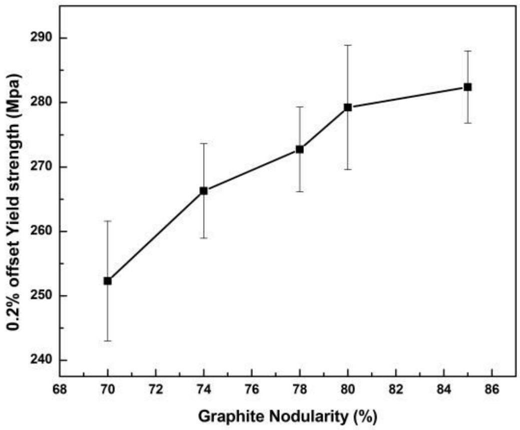


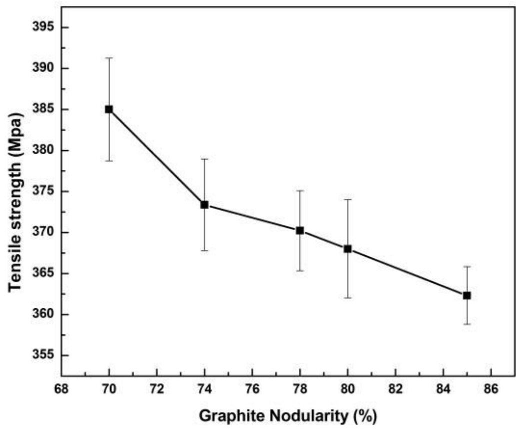
(Fig. 5.13e Microstructure of melt S5, 100X)

Specimens used for metallographic analysis in the as-cast condition were ground, polished and etched with 2% nital. After etching, the specimens were examined by means of digital image analyzer from images taken in an optical microscope. The nodularity was determined by the ratio between the number of type I and II (nodular) graphite particles (ASTM A247) and the total number of graphite particles. The graphite phase of each specimen was analyzed with regard to the roundness, nodularity and fraction [34].

The microstructure of typical commercial heavy section as-cast SG iron casting consists of graphite nodules embedded in a ferrite shell and of pearlite. This is so called bull's eye structure. The control of this microstructure is of practical importance because it determines the mechanical properties of the casting. The microstructure evolves during cooling. Austenite decomposes to give ferrite and graphite. Ferrite nucleates at the graphite/austenite interface and then grows symmetrically around the nodules [102]. The precipitation of graphite (fig. 5.13a to 5.13e) during solidification results in a volume expansion and mass flow, and furthermore in shrinkage defects accompanying the freezing of spheroidal graphite iron. The nucleation and growth kinetics of the graphite affects the volume change significantly. Growth rate of graphite and austenite are mainly the two factors for volume change. Silicon promotes the graphitization process significantly [103]. From the phase morphologies analysis (table 5.13 and fig. 5.13a to 5.13e), it is observed that ferrite starts to nucleate and grow mainly at the graphite nodule interface (fig. 5.13c) and also at the grain boundaries (fig. 5.13d). For the melt S5, it is observed that ferrite nucleates and starts growing mainly at the austenite grain boundaries. This changes the characteristics of the $\gamma \rightarrow \alpha$ transformation. Ferrite morphology changes with the changes in basic composition as a result of carbon diffusivity [72].

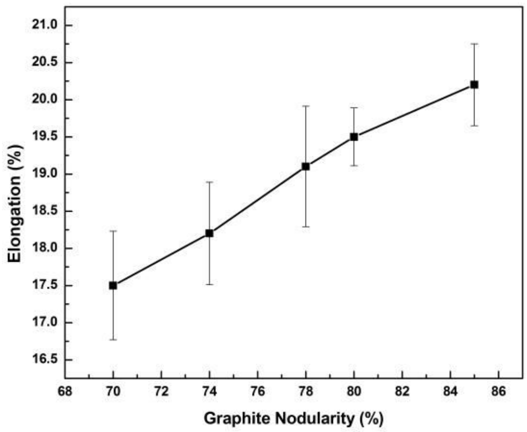
The as-cast tensile properties and impact strength (at -20^oC) were measured and found as a function of nodularity as illustrated in fig.5.13f, fig. 5.13g, fig. 5.13h and fig.5.13i respectively.

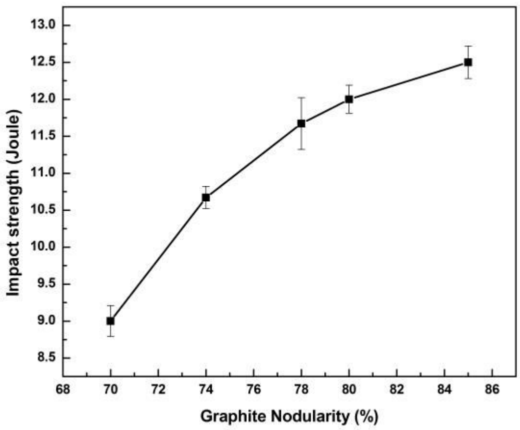




(Fig. 5.13f Effect of graphite nodularity on tensile strength)

(Fig. 5.13g Effect of graphite nodularity on yield strength)





(Fig. 5.13h Effect of Graphite nodularity on Elongation)

(Fig. 5.13i Effect of graphite nodularity on Impact strength)

It is observed from the current study that with the increase in graphite nodularity, the tensile strength decreases where as yield strength increases. Similarly, with the increase in graphite nodularity, the elongation and impact strength increases as observed in Fig. 5.13h and fig. 5.13i respectively. The graphite morphology plays an important role and more the graphite shapes deviates from the ideal spherical shape the lower is the ductility and strength. The difference in strength properties for different graphite nodularity levels may be due to the easier crack propagation with lower degree of graphite morphology. The impact strength of SG iron is influenced significantly by the matrix structure and the testing temperature. All the matrix structures have energy values which decrease with decreasing the testing temperature. Ductile iron with ferritic matrix (fig.5.13d and fig. 5.13e) exhibits more impact energy than the melt no S1, S2 and S3. As the pearlite content (table 5.13) increased (from melt no. S3 to S1), the impact energy decreased. It may be note that when the ferritic matrix structure transforms into the pearlitic structure due to change in basic composition of the melt, the impact energy is decreased by at least 50% for all temperatures. The decrease of impact energy in the pearlitic matrix is more than that in ferritic matrix at subzero temperatures [34-35].

In the present investigation, the experiment was carried out on heavy section ductile iron castings. The ferrite has a good ductility (table 5.1b and table 5.13) and possesses ability to resist the fall in impact energy at low temperatures. The presence of small amount of residual pearlite in the ferrite matrix may influence the mechanical properties of SG iron. It increases the material hardness (138 BHN for the melt no.S1) and reduces the impact energy (9 joule for the melt no. S1). The impact energy is also affected by graphite nodularity. If the spherulite is larger in size or if the nodule count increases, the mechanical property decreases accordingly. From the results it is evident both ferrite content in the matrix and the graphite morphology can influence the impact energy [2-4, 99].

5.2 Influence on mechanical properties & matrix structure with the addition of Nickel

Ductile cast iron exhibits good mechanical properties because of the spheroidal graphite present in the matrix. It has been found in the literature that the strengthening and toughening of ductile iron result from the modification of the matrix structure when alloying elements are added or certain heat treatment is applied [101]. Each alloy element present in the melt influences in a different way in mechanical properties in the cast [104]. Nickel element has no solubility limit to iron and it produces single phase of austenite when added for more than 30%. In the present investigation, five melts of different wt% of nickel were produced as per standard foundry practices. Special care was taken during controlling of process parameters in order to get defect free casting. Since the objective was to improve the mechanical properties in as-cast condition, the appropriate balance of the alloying elements was made during production of the casting. As per EN1563 standard, all the five melts were machined and polished for determination of tensile properties and microstructural analysis. The chemistry of the melt and tensile properties are illustrated in table 5.2a and 5.2b respectively

Table 5.2a Chemical Composition of the melts (N1 to N5) in wt%.

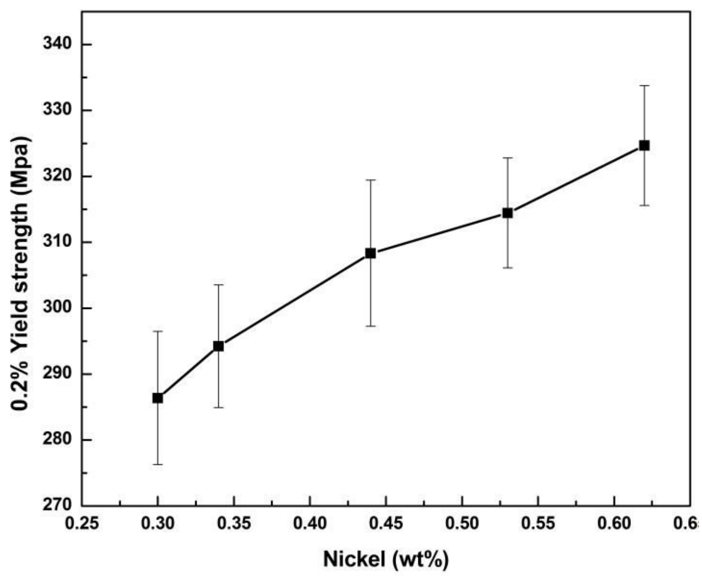
Melt no.	C	Si	Mn	S	P	Cr	Ni	Cu	Mg
N1	3.60	2.08	0.15	0.014	0.021	0.011	0.30	0.018	0.046
N2	3.58	2.09	0.16	0.015	0.023	0.015	0.34	0.020	0.048
N3	3.62	2.12	0.18	0.014	0.020	0.013	0.44	0.019	0.047
N4	3.60	2.08	0.16	0.016	0.024	0.012	0.53	0.022	0.050
N5	3.59	2.10	0.18	0.010	0.023	0.014	0.62	0.021	0.046

Table 5.2b Mechanical Properties of the melts (N1 to N5)

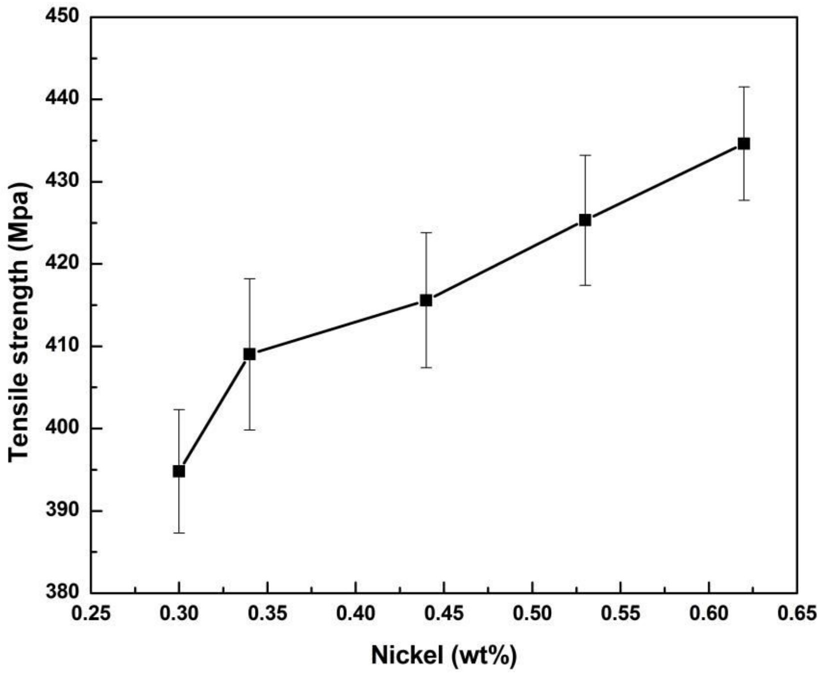
Melt No.	0.2% YS (Mpa)	UTS (Mpa)	Elongation (%)	Impact Strength (at -20^{0}C)(Joule)	Hardness (BHN)
N1	286.36 (±10.1)	394.81 (±7.5)	16.21 (±0.45)	10 (±0.12)	185 (±3.5)
N2	294.22 (±9.3)	409.03 (±9.2)	15.42 (±0.56)	9.5 (±0.13)	192 (±3.1)
N3	308.34 (±11.1)	415.58 (±8.2)	14.51 (±0.32)	9.2 (±0.14)	196 (±2.1)
N4	314.44 (±8.35)	425.32 (±7.9)	14.21 (±0.54)	8.6 (±0.09)	200 (±2.8)
N5	324.67 (±9.1)	434.62 (±6.9)	13.84 (± 0.45)	8.4 (± 0.085)	208 (±3.2)

5.21 Effect of Nickel on Tensile Properties

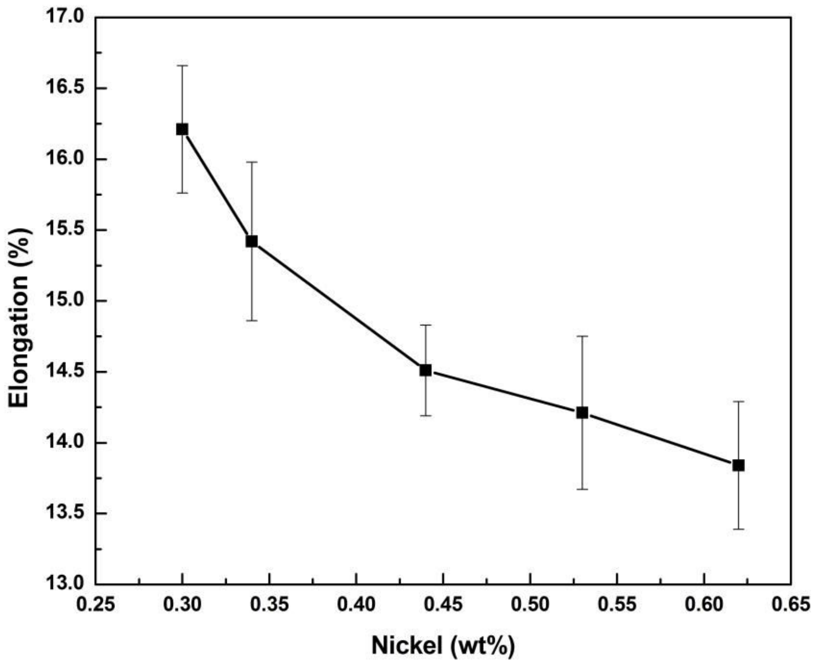
The impact values shown in the table 5.2b are the average values of three samples tested at -20^{o}C. The chemical composition was so balanced that it is easy to observe the influence of nickel on the mechanical properties and microstructural characterization of the as-cast heavy section castings. The influence on 0.2% offset yield strength, tensile strength, elongation, Impact properties at subzero temperature and hardness are shown in the fig.5.21a, 5.21b, 5.21c,5.21d and 5.21e respectively.



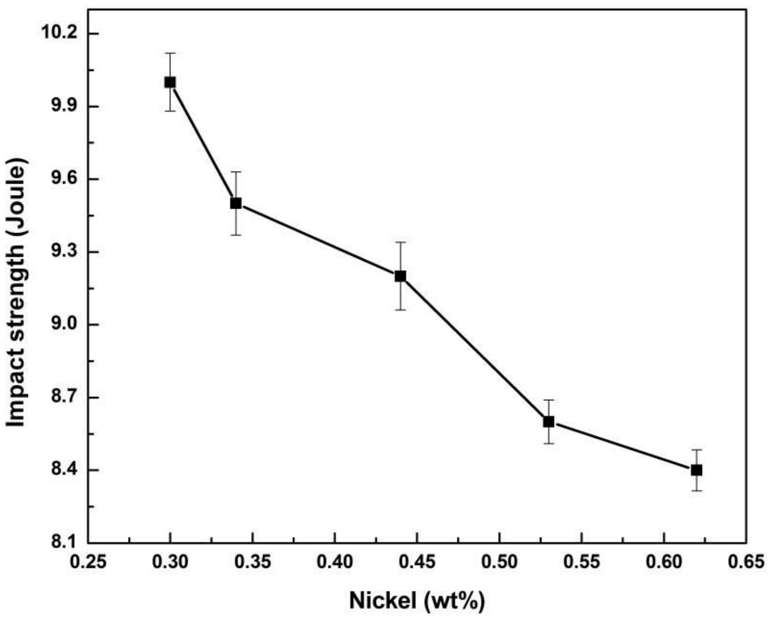
(Fig.5.21a Effect of Nickel on 0.2% Yield strength)



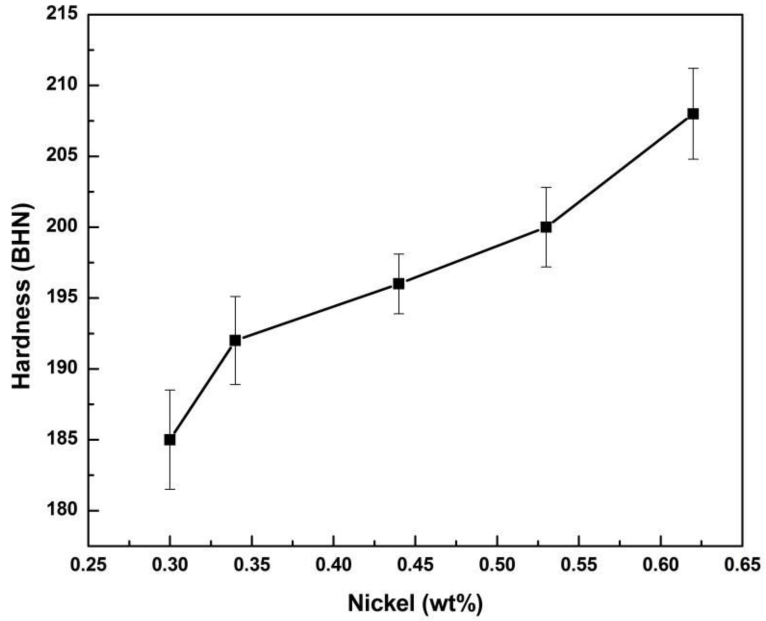
(Fig.5.21b Effect of Nickel on Tensile Strength)



(Fig.5.21c Effect of Nickel on Elongation)



(Fig.5.21d Effect of Nickel on Impact Strength)



(Fig.5.21e Effect of Nickel on Hardness)

It is observed that with increase in nickel content in the melt, the 0.2% offset yield strength (Fig 5.21a), tensile strength (Fig.5.21b), and hardness (fig.5.21e) increases. Whereas the impact strength (Fig.5.21d) decreases very slightly and ductility (fig.5.21c) decreases with increase in nickel content. This may be due to mild pearlite promoter property of nickel.

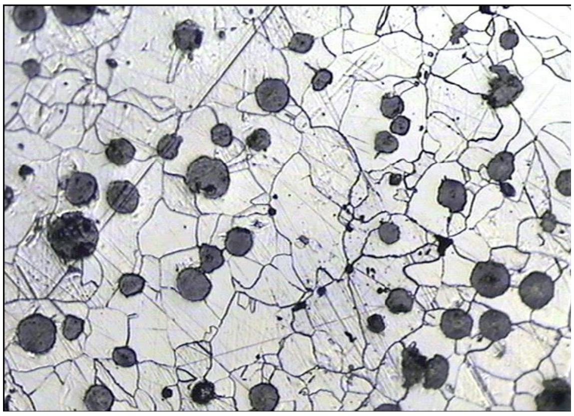
Since the pearlite content in the matrix increases, the hardness, tensile strength and yield strength increases where as elongation and impact value decreases.

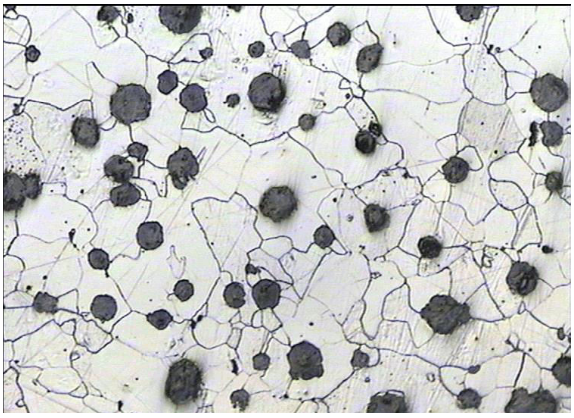
5.22 Microstructural Characterization (Melt No. N1 to N5)

The specimens for the microstructural analysis were prepared as per standard practice. The specimens were ground; polished and etched with 2% nital solution. The microstructural analysis was carried out in the digital image analyzer for the melt nos. N1 to N5. The results are illustrated in table 5.22 and the microstructures are shown in fig. 5.22a, 5.22b, 5.22c, 5.22d and 5.22e respectively for the melt nos. N1 to N5. From the microstructure it is observed that the graphite spheroids are embedded in the ferrite matrix of pearlite. If the matrix structure of the soheroidal graphite iron shows a pearlite content ranging from 10 to 60% then the iron is called ferritic-pearlitic ductile iron [26]. The correlation between tensile properties and pearlite content of all the melts are shown in the fig.5.22f, fig.5.22g, fig.5.22h, fig.5.22i and fig5.22j. The pearlite content is varied from 10% to 20% by the addition of nickel in the molten metal in different wt% (table 5.2a). The apparent variation in tensile properties is due to matrix structure.

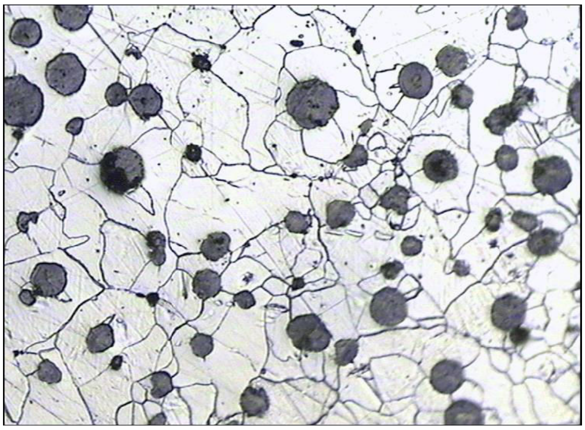
Table 5.22 Microstructure Description (melt No. N1 to N5)

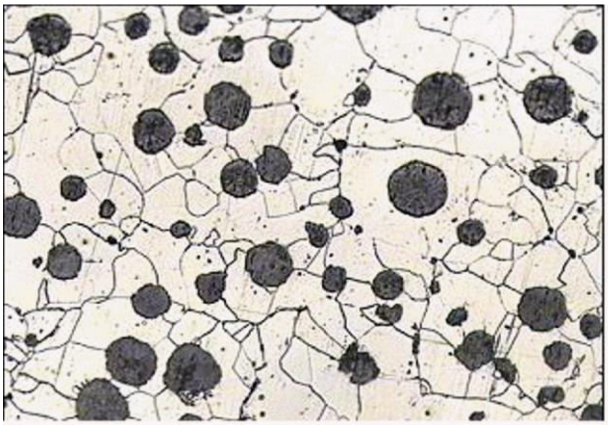
Melt No.	**Matrix**	**Nodularity (%)**	**Nodule count (nos/mm^2)**
N1	90% ferrite, 10% pearlite	86	167
N2	88% ferrite, 12% pearlite	88	192
N3	86% ferrite, 14% pearlite	91	203
N4	82% ferrite, 18% pearlite	94	184
N5	80% ferrite, 20% pearlite	96	196



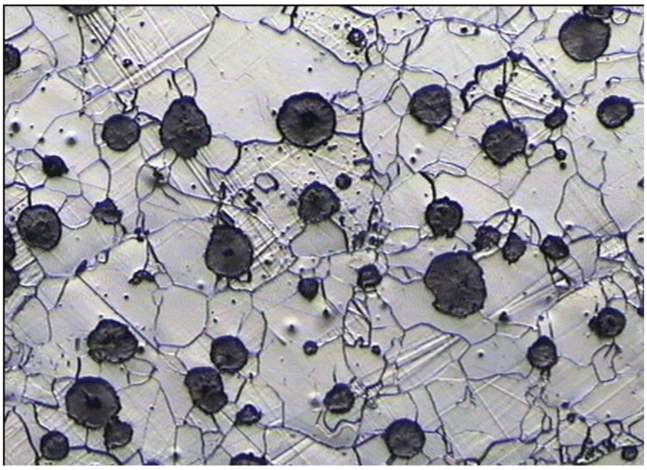


(Fig.5.22a Microstructure of melt N1, 100X) (Fig.5.22b Microstructure of melt N2, 100X)

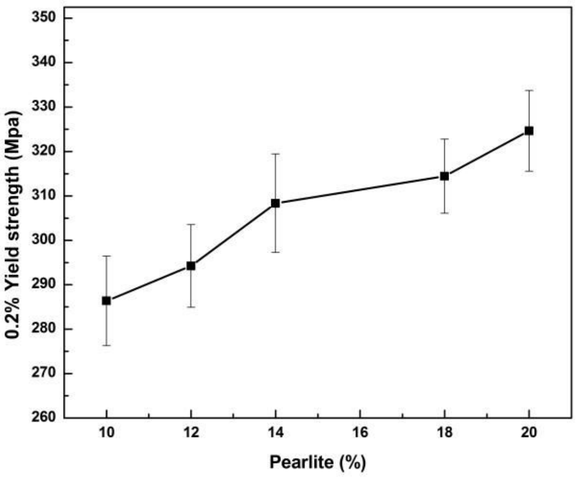


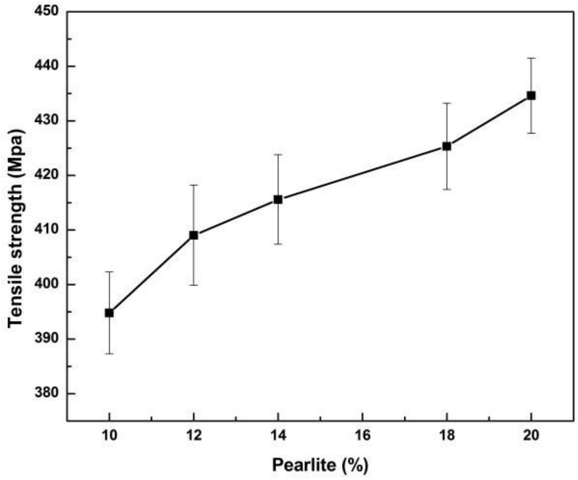


(Fig.5.22c Microstructure of Melt N3, 100X) (Fig.5.22d Microstructure of Melt N4, 100X)

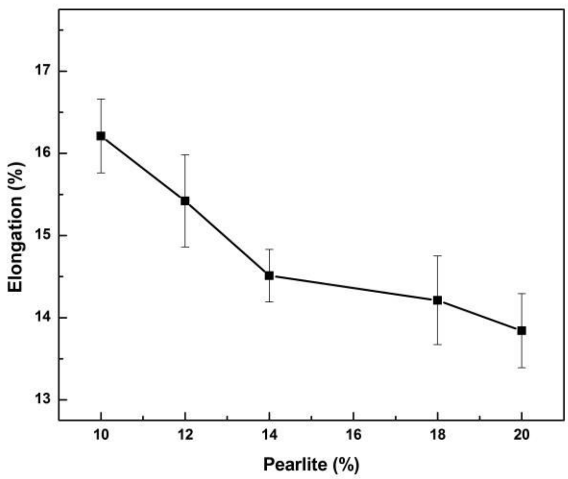


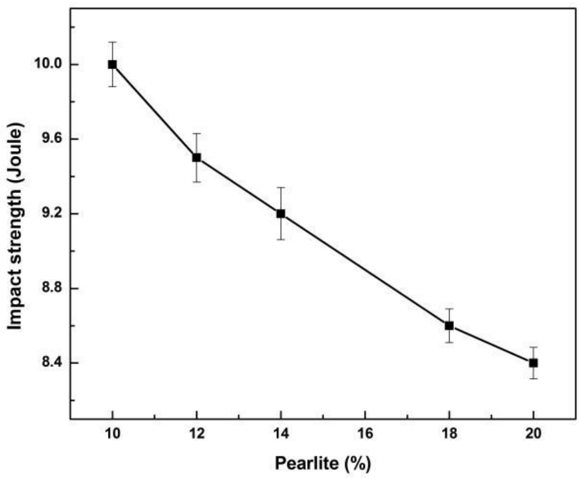
(Fig.5.22e Microstructure of Melt N5, 100X)



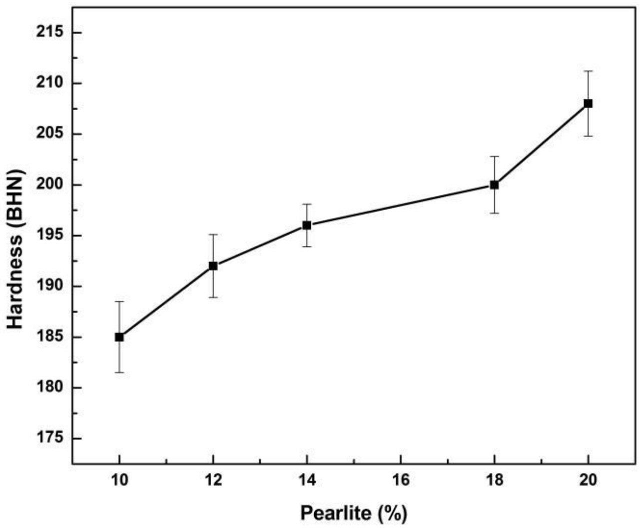


(Fig.5.22f Effect of pearlite content on 0.2% YS)   (Fig.5.22g Effect of pearlite content on Tensile strength)





(Fig.5.22h Effect of Pearlite content on Elongation)   (Fig.5.22i Effect of Pearlite content) on Impact Strength)



(Fig.5.22j Effect of Pearlite content on Hardness)

It is observed (table 5.2b) that the 0.2% yield strength ranges from 286.36Mpa to 324.67 Mpa for a ferritic matrix of pearlite. The ultimate tensile strength (fig.5.22g) for the present nickel alloyed SG iron is increased due to increase in pearlite level. The ductility (fig.5.22h) and impact strength (fig.5.22i) are also decreased with increase in Pearlite content. As shown in the fig.5.22i, ductile iron with 90% ferritic and 10% pearlite matrix exhibits the highest energy (10 Joule) and other samples shows less fracture energy. The fracture energy of ductile iron is significantly influenced by the presence of microsonstituents in the metallic matrix and the hardness of the material depends upon the matrix structure. Fig.5.22j provides an evidence of the relationship between Brinell hardness and pearlite content in as-cast spherulitic graphite iron castings. It is also observed that (fig.5.22j) the hardness value of the present material is increased with the increase in pearlite content in the matrix [26]. The impact strength of ductile iron is influenced by the matrix structure and the testing temperature. The present material was tested at -20^{0}C and from fig.5.22i it is observed that with increase in pearlite content, the impact strength decreases. It may be noted that when the ferrite matrix structure transforms into the pearlite structure by alloy addition in the melt, the impact energy decreases [35]. The as-cast microstructure (fig.5.22a to 5.22e) depends on the solidification process and section thickness followed by subsequent solid state transformation. The inoculation practice followed and the cooling rate plays a vital role for controlling nodule count whereas the matrix microstructure depends on the conditions under which eutectoid reaction occurs. Hence a number of parameters influence the as-cast microstructure of the spheroidal graphite iron for thick-walled castings [60]. The literature suggests that graphite spheroids in a ferritic matrix prove good ductility, tensile strength, yield strength and impact resistance that is equivalent to the properties of low carbon steel. In case of a ferrite-pearlitic matrix, the spheroidal graphite provides properties intermediate between ferrite and pearlite grades with good machinability and low cost production [26]. As shown in table 5.2a and table 5.2b, the small additions of nickel (varying wt % from N1 to N5) changed the as-cast mechanical properties owing to the different as-cast microstructures (Fig.5.22a to 5.22e). The increased in nickel contents developed some fractions of pearlite structures near the austenite eutectic cell boundaries which caused impact energy and ductility (fig.5.22h and 5.22i) to drop in a small range. As shown in fig 5.21b, with the increase in amount of nickel addition tensile strength is increased while elongation is decreased (fig.5.21c). The decrease in ductility is caused by the increase in pearlite content (table 5.22 and fig.5.22h) in the matrix. The strength of nickel alloyed ductile iron mainly depends on the solid solution hardening of ferrite matrix [101]. Figure 5.21d and 5.21e shows the variation in hardness and impact energy with different amount (wt %) of nickel additions.

5.3 Influence on Mechanical properties & Matrix structure with the addition of Copper

The influence of copper on the mechanical properties of as –cast spheroidal graphite cast iron depends very considerably upon the subversive element content of the materials. The effect of copper on the formation of nodular graphite is not completely understood.

Copper appears to make nodular cast irons more sensitive to the effect of subversive elements. When copper is added in the melt at low level for the production of SG iron, the decomposition of austenite to ferrite plus graphite is favoured. This decomposition occurs at a lower temperature than that in the base alloy. At higher level, copper acts as strong pearlite promoter [102]. The common alloying elements used to control matrix (ferrite/pearlite)of the SG iron are Si, Mn and Cu. Copper is used to promote pearlite. Higher percentage of pearlite content in the matrix of SG iron shows higher hardness value which is mainly responsible for poorer machinability [105]. The effect of copper on the mechanical properties and microstructure of heavy section as-cast ductile iron casting was studied in this investigation. Five melts with different weight % of copper was added in the melt during production of the castings. The standard foundry practices were followed and all the basic parameters were monitored in order to get quality casting. The samples were taken from the centre of the castings for tensile properties measurement. The samples were machined and ground as per EN1563 specification for tensile properties. V-notched charpy impact test was also performed at -20^{o}C. The average results of charpy impact values of three specimens were taken in to consideration. Hardness of the specimens was measured. The chemical composition of the melts is listed in table 5.3a and the tensile properties are listed in table 5.3b.

Table 5.3a Chemical Composition of the melts in wt % (Melt no. C1 to C5)

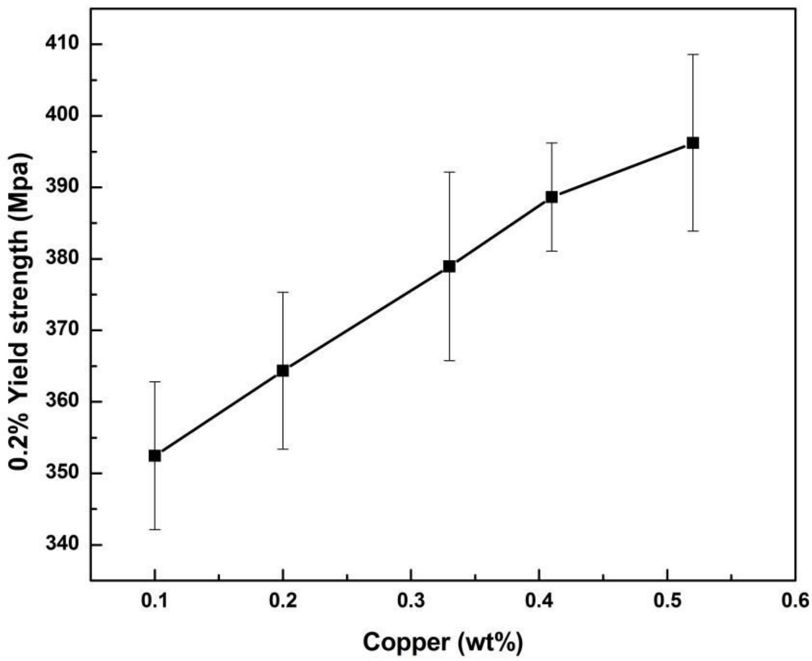
Melt No.	**C**	**Si**	**Mn**	**S**	**P**	**Cr**	**Ni**	**Cu**	**Mg**
C1	3.60	2.08	0.23	0.009	0.021	0.015	0.022	0.10	0.044
C2	3.59	2.06	0.21	0.008	0.023	0.018	0.020	0.22	0.046
C3	3.56	2.05	0.23	0.008	0.022	0.020	0.030	0.33	0.043
C4	3.58	2.07	0.22	0.009	0.023	0.022	0.030	0.41	0.045
C5	3.60	2.09	0.23	0.010	0.022	0.020	0.020	0.52	0.044

Table 5.3b Mechanical properties of the melts (Melt no. C1 to C5)

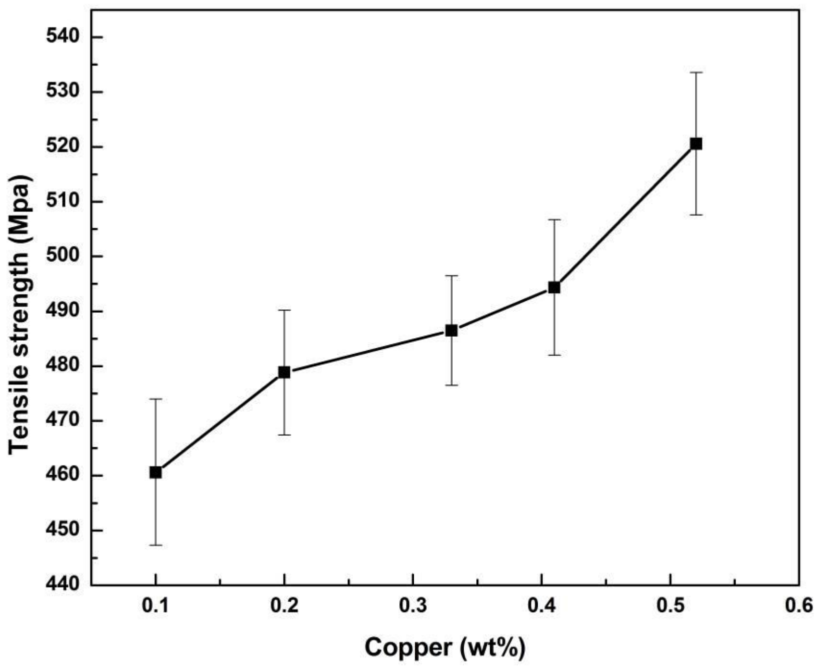
Melt No.	0.2% YS (Mpa)	UTS (Mpa)	Elongation (%)	Impact Strength (at -20°C) (Joule)	Hardness (BHN)
C1	352.46 (±10.35)	460.62 (±13.35)	9.20 (±0.65)	7.20 (±0.24)	210 (±9.30)
C2	364.32 (±10.98)	478.82 (±11.38)	8.60 (±0.56)	6.40 (±0.19)	224 (±10.23)
C3	378.94 (±13.2)	486.46 (±9.98)	7.20 (±0.43)	5.60 (±0.18)	232 (±11.32)
C4	388.64 (±7.56)	494.36 (±12.35)	6.50 (±0.29)	5.20 (±0.22)	244 (±8.35)
C5	396.22 (±12.34)	520.58 (±12.98)	6.20 (±0.35)	4.80 (±0.11)	252 (±7.66)

5.31 Effect of Copper on Tensile Properties

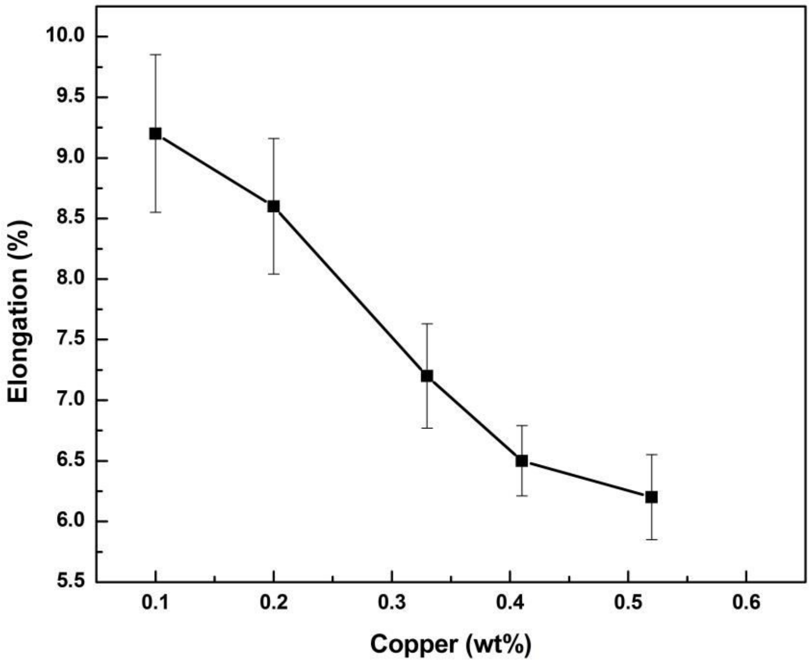
Table 5.3a and 5.3b gives the analysis and mechanical properties of the copper alloyed melts (melt no. C1 to C5). Hardness was measured on the broken tensile specimens. The V-Notched Charpy Impact strength was measured at -20°C and the result was obtained by taking average impact values of three specimens of the same sample. The small addition of copper changed the as-cast mechanical properties owing to the different as-cast matrix microstructures. Adding copper rapidly changed the ferrite matrix into pearlite matrix. The strength and hardness of the castings are significantly increased [99, 101]. The variation of 0.2% yield strength, tensile strength, elongation, impact strength at -20°C and hardness with different wt% of copper are shown in the fig.5.31a, 5.31b, 5.31c, 5.31d and 5.31e respectively. As shown in fig.5.31a, 5.31b and 5.31e, the yield strength, tensile strength and hardness are increases with increase in copper content in the melts. Whereas ductility and impact strength at subzero temperature decreases with increase in copper.



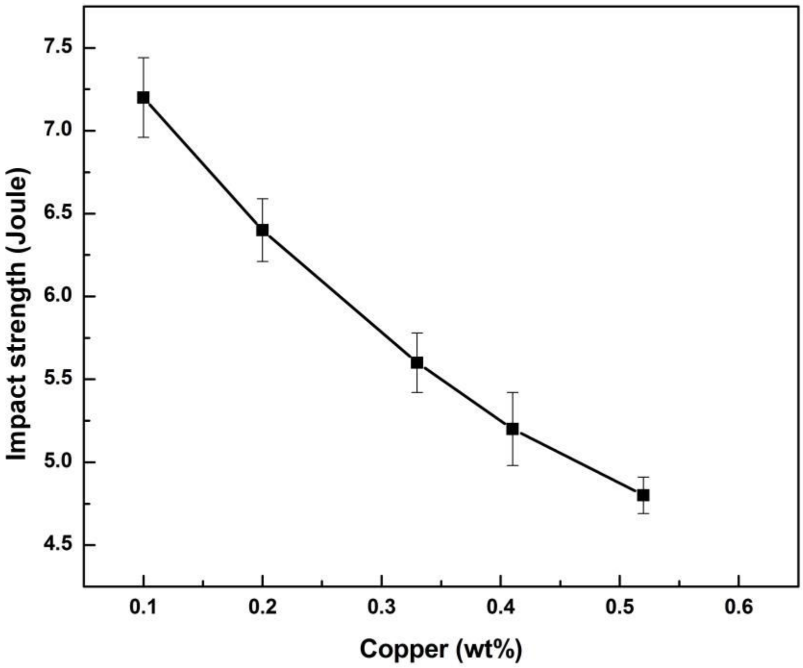
(Fig.5.31a Effect of Copper on 0.2% YS)



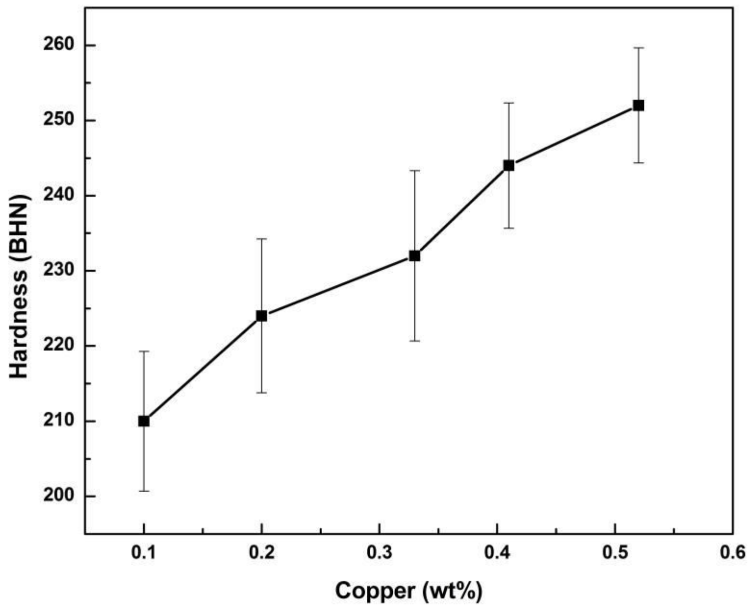
(Fig.5.31b Effect of Copper on Tensile Strength)



(Fig.5.31c Effect of Copper on Elongation)



(Fig.5.31d Effect of Copper on Impact Strength)



(Fig.5.31e Effect of Copper on Hardness)

The effect of copper and the section thickness also influences the volume fraction of pearlite. Increasing the copper content from 0% to 0.5% resulted in an increase in approximately 30% to 55% pearlite for thick-walled ductile iron castings. The amount of pearlite in the matrix of the melt and casting thickness are related by a relation (eqn...1) as follows [52].

Pearlite = $\frac{1}{4}[192Cu - x + 122]$ .... (1)

For 0% < Cu < 1% and 10mm < x < 50mm, where x is the thickness of the castings in mm.

The influence of copper on the mechanical properties is complex and depends upon whether the iron contains subversive elements such as titanium, in which case even as little as 1percent (wt%) copper can cause the formation of substantial amounts of flake graphite. The harmful effects introduced by copper can be neutralized by the addition of small amount of cerium. Cerium acts both as an inoculant and nodularizer. It reacts with both dissolved oxygen and sulphur in the cast iron melt and forms the inclusions of the type X_2Y_3 and XY_2

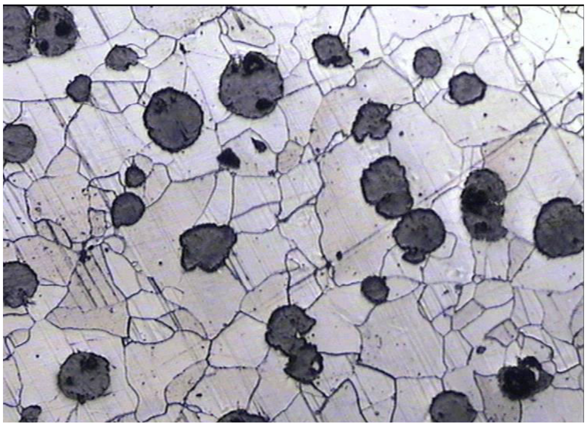
where X is cerium and Y is either Sulphur or Oxygen [3-4, 104-106]. An excess of cerium in cast iron may cause formation of undesired graphite structures and carbides, especially in ductile iron. Exploded and chunky graphite forms can occur and both these lead to reduce mechanical properties. This problem especially found in heavy section ductile iron castings. Copper in the molten metal favours the formation of pearlite or iron carbide. So excess addition of copper should be carefully controlled to avoid the detrimental effect on ductility [107]. Figure 5.31b shows the variation of tensile strength with the addition of copper. The tensile strength of 0.52wt% copper added ductile iron approaches at a maximum of 521 MPa, but elongation quickly decreases (fig.5.31c) to 6.2%. It may be confirmed that the tensile strength of as-cast ductile iron casting strongly depends on the volume fraction of pearlite where as ductility is inversely proportional to the pearlite fraction in the as-cast microstructure [101]. Figure 5.31d and 5.31e shows the variation of Charpy impact energy and hardness of the as-cast thick-walled ductile iron castings with different wt% of copper. Generally the hardness is increased by the volume fraction of the pearlite structure. With increase in copper addition (melt no. C1 to C5), the hardness increased significantly owing to the high fraction of pearlite. The Charpy impact energy is gradually decreased. Comparing the ferrite, pearlitic/ferritic and pearlitic structures, it is well understood that as the pearlite content in the matrix increases, the hardness of the as-cast ductile iron casting also increases [35].

5.32 Microstructural Characterization (melt no. C1 to C5)

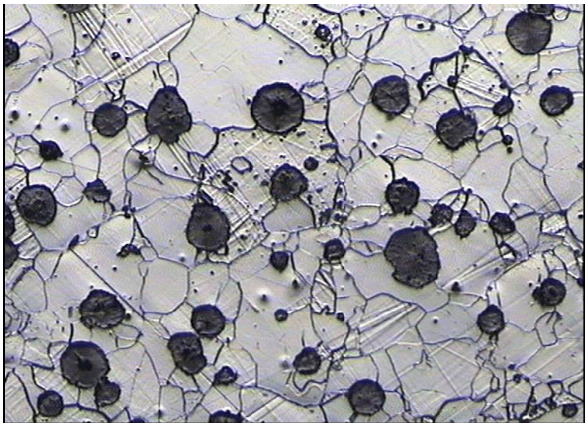
Specimens used for metallographic examination in the as-cast condition were ground, polished and etched with 2% nital solution. After etching the specimens were analyzed under digital Image Analyzer. The quantitative measurement of the structure feature is shown in table 5.32. The microstructure of the melts from C1 to C5 is shown in fig.5.32a, 5.32b, 5.32c, 5.32d and 5.32e respectively. A correlation has been made between tensile properties and pearlite content of the melts and is shown in fig.5.32f, 5.32g, 5.32h, 5.32i, 5.32j.

Table 5.32 Microstructure Description (Melt No. C1 to C5)

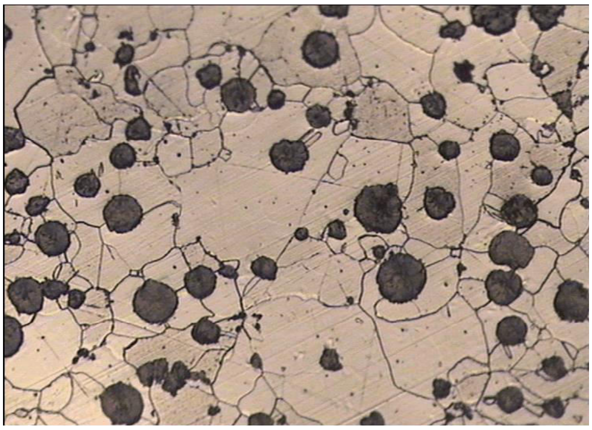
Melt No.	**Matrix**	**Nodularity (%)**	**Nodule Count (nos./mm^2)**
C1	78% ferrite, 22% pearlite	84	140
C2	75% ferrite, 25% pearlite	88	132
C3	73% ferrite, 27% pearlite	90	150
C4	70% ferrite, 30% pearlite	93	144
C5	66% ferrite, 34% pearlite	88	180

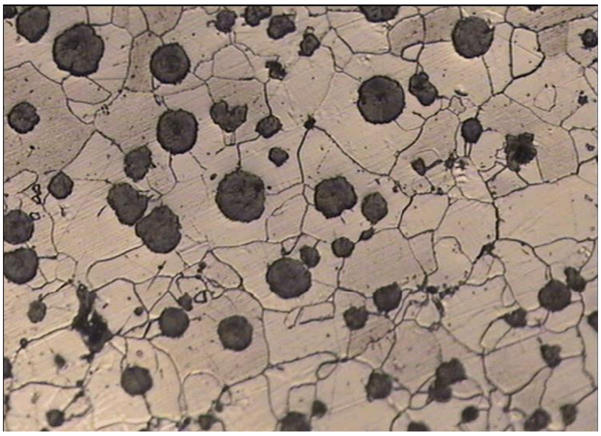


(Fig.5.32a Microstructure of Melt C1, 100X)

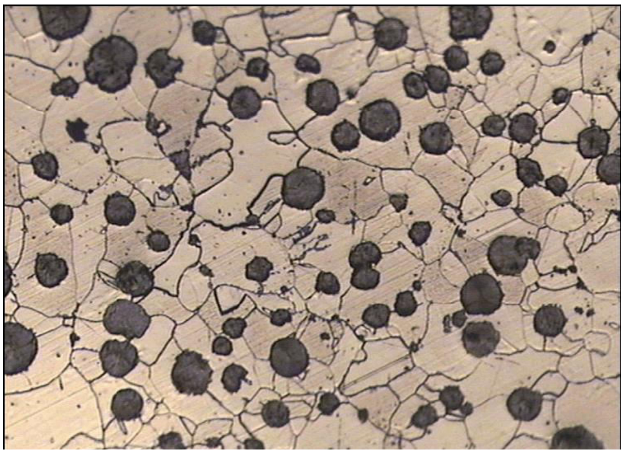


(Fig.5.32b Microstructure of Melt C2, 100X)



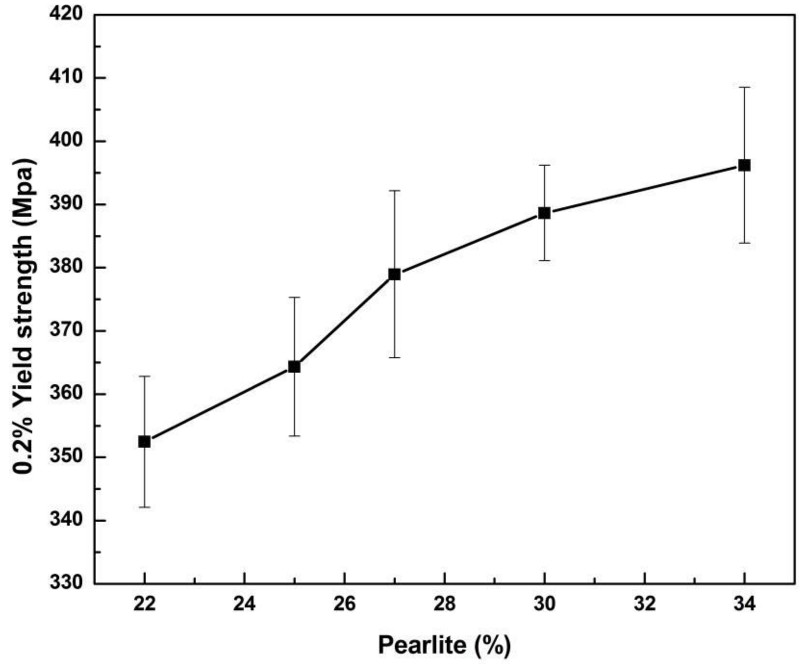


(Fig.5.32c Microstructure of Melt C3, 100X) (Fig.5.32d Microstructure of Melt C4, 100X)

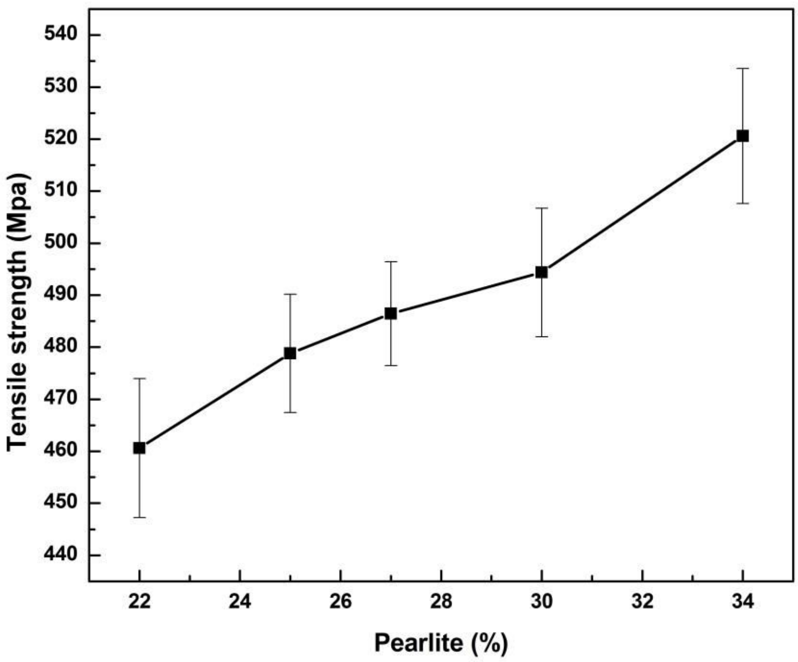


(Fig.5.32e Microstructure of Melt C5, 100X)

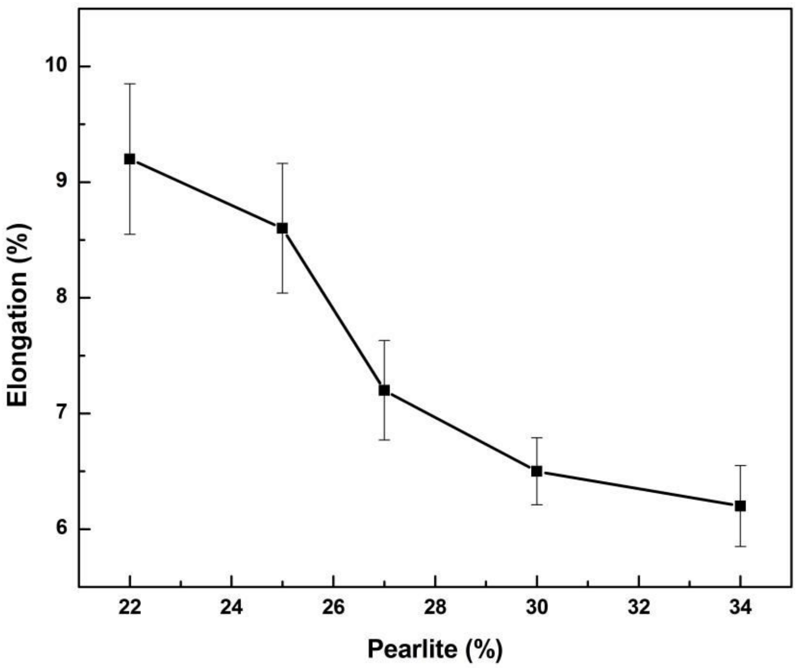
From the microstructure, it is observed that all of these irons (Melt no. C1 to C5) had good nodular structure. Melt no. C1 with 0.10wt% copper had a matrix of 78% ferrite and 22% pearlite (table 5.32). From the melt C1 to C5, the pearlite percentage increased from 22% to 33% with the addition of copper from 0.10wt% to 0.52wt% respectively. Since adding copper in to the melts, the ferrite matrix got changed into pearlite matrix, so strength and hardness were significantly increased (fig.5.31a, fig.5.31b and fig.5.31e).As more copper is added (melt no. C5), the ferritic structure is significant and pearlite % increased to 33%. The copper will increase the strength and hardness in as-cast heavy section ductile iron castings through increased pearlite formation [97, 99, 101]. The presence of pearlite in the metallic matrix of the ductile iron influenced the tensile properties as shown in the figures (fig.5.32f, 5.32g, 5.32h, 5.32i, 5.32j) as follows.



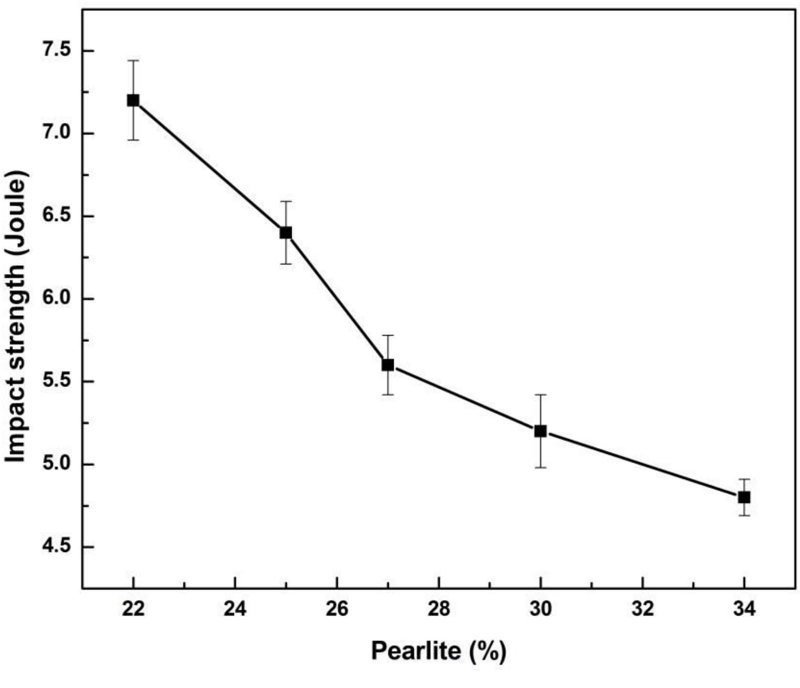
(Fig.5.32f Effect of Pearlite content on 0.2% Yield Strength)



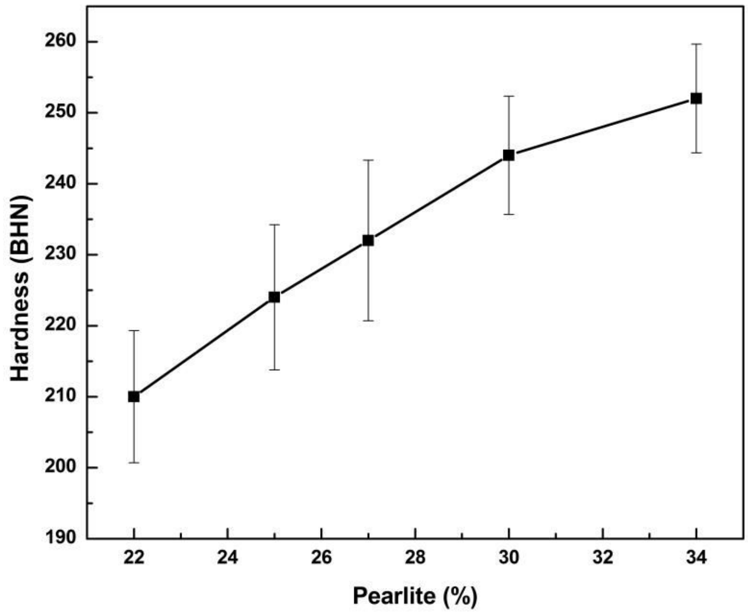
(Fig.5.32g Effect of Pearlite content on Tensile Strength)



(Fig.5.32h Effect of Pearlite content on Elongation)



(Fig.5.32i Effect of Pearlite content on Impact Strength)



(Fig.5.32j Effect of Pearlite content on Hardness)

The most common features in all the ductile iron is the graphite are the roughly spherical shape. The volume percentage of graphite phase embedded in the ductile iron is around 10-15%. The mechanical properties of SG iron are influenced by the matrix structure. Some variables like chemical composition and cooling rate are controlling the matrix [35]. The pearlitic ductile iron has graphite spheroids in the matrix of the pearlite. Pearlite is a fine lamellar aggregate of ferrite and cementite. The alloy containing pearlite matrix is relatively hard with moderate ductility and high strength [105]. Fig.5.32f and Fig.5.32g shows the variation of yield strength and tensile strength with Pearlite content. Both the yield strength and tensile strength increases with increase in pearlite content whereas a fig.5.32h and fig.5.32i show there is decrease in elongation and Charpy impact energy with the increase in pearlite content. Fig.5.32h shows the increase in hardness value with the increase in pearlite content. The pearlite has the property to harden the matrix and at the same time, the increased pearlite content enhances the resistance of the matrix. The pearlite matrix shows very low impact energy of about 4.8J (melt no.C5). The presence of pearlite in the matrix of the iron was more effective for the property enhancement of ductile iron [99]. The hardness of SG iron depends upon the matrix structure and increase with increase in pearlite content (fig.5.32j). This can be attributed to the effect of copper for the promotion of pearlite in the matrix of SG iron which affects the hardness of the pearlite phase and thus the hardness of the material [26]. The hardness of the cast iron is generally increased with increase in volume fraction of the pearlite content. The addition of copper with different percentage in the melt, the Charpy impact values and ductility decreases due to pearlite content in the matrix (fig.5.32i and fig. 5.32h) which indicates that ferrite matrix provides highly ductile cast iron while pearlite matrix provides highly strong cast iron [101].

When a comparison was made between the Ni and Cu content SG iron samples with respect to pearlite content, some points were outlines. In the sample from N1 to N5, the Ni % varies from 0.30 to 0.60 and from C1 to C5; the Cu% varies from 0.10 to 0.52. The results of tensile properties as well as microstructural analysis are listed in table 5.2b, 5.3b, 5.22 and 5.32 respectively. Since both Ni and Cu are pearlitic promotor, the tensile properties viz., 0.2% YS, UTS, and hardness increases with increase in pearlitic content where as impact strength and ductility decreases. From the table 5.22 and 5.32, It is clearly observed that the pearlitie percentage in the matrix for the sample C1 to C5 is much more than the sample fromN1 to N5. This is the reason why SG irons with Cu shows more 0.2%YS, UTS and hardness values than SG iron containing Ni. Whenever a comparision is made between effect of Ni and Cu on tensile properties of SG iron with reference to pearlite content, a stament was made that pearlite percentage in Cu content specimens (C1 to C5) varies from 22 to 34 where as pearlite percentage in Ni content specimens (N1 to N5) varies from 10 to 20 resulting in lower tensile properties as compared to previous one. However the impact strength and ductility drastically reduced for the samples C1to C5 as compared with N1 to N5.

It may be noted that if Ni and Cu concentration are such that both the samples have same or nearly same pearlitic content (N5 and C1), then the mechanical properties as well as graphite morphology are not similar, the reason behind is, both Ni and Cu has individual properties and both have different rate of peralitic promotion in the matrix during solidification. The matrix of Ni content SG iron is softer than that of Cu content SG iron. On the other hand, the influence of copper on the mechanical properties is complex and depends upon whether the iron contains subresive elements such as titanium. In the equal or nearly equal percentage of pearlite, the Ni content sample behaves somewhat more ductile than the Cu content sample.

Chapter-6

6. Conclusions

In the present investigation, a clear objective was made to improve the mechanical properties of spheroidal graphite iron castings in as-cast condition for heavy section size by alloying with nickel and copper. Ductile iron is characterized by having all its graphite in spherulitic forms. Although this graphite constitutes about 10-15% by volume of DI, its compact spherical shape minimizes the effect on mechanical properties. The graphites in the commercially produced SG iron are not always in perfectly spherical shape. It can occur in a somewhat irregular form, but if it is still chunky as type II in ASTM A247 standard, the properties of the iron will be similar to cast iron with spheroidal graphite. Of course, further degradation can influence mechanical properties. The shape of the graphite is established when the metal solidifies and it cannot be changed in any way except by re-melting the metal. The improved mechanical properties increase its resistance to breakage from physical load that of gray iron and its corrosion resistance property is superior to that of gray cast iron and cast steel. Its wear resistance property is comparable to the best grades of steel and gray iron. The substantial advantages of SG iron are its high yield strength and ductility which make it an economical choice for many applications.

It is well known that to achieve high ductility and high strength in the same casting materials is not possible in as-cast condition which needs alloying of the materials with different alloying elements. In this study, three types of SG iron (without Ni & Cu, with Ni and With Cu) were produced with varying alloying element addition. Experimental work was carried out to study the effect of graphite, nodule count, nodularity, pearlite on the mechanical properties. A correlation was made between mechanical properties and matrix microstructure. The following conclusions could be drawn from the present investigation.

- In all three types of ductile iron production, section size plays an important role on the property characterization of SG iron in as-cast condition.
- Silicon as a ferrite promoter has the greatest effect on mechanical properties. Both the yield strength and tensile strength as well as ductility increases with increase in silicon content where as hardness of the material get decreased due to ferritic matrix of the structure.
- SG iron retains its ductility up to the silicon addition 2.4wt%. More than that, the materials exhibits DBT (Ductile –to-Brittle transition) and possess brittle properties.
- Production of SG iron by the process described in this investigation may represent a good understanding in the field of metallurgy of cast iron.
- Copper has the greatest effect on tensile properties but has little effect on impact properties at subzero temperature. Introduction of copper at high amount ($\geq$ 0.80 wt %) produces adverse effect on the tensile properties, but by using Cu-Mg-Ce alloys this danger will be avoided.
- The inoculation technique followed in this investigation is of indispensable for commercial utility.
- The graphite nodularity in all the tree types of DI is found above 80% and nodule count ranges from 100-225 nos/mm^2 because of heavy section size.
- Presence of trace elements like antimony, bismuth, lead, arsenic, indium, tin and lanthanum promoted the formation of pearlite in the as-cast structure as studied from melt chemistry and microstructural characterization.

- The late inoculation process introduced in the present investigation produces nucleation centres of nodular graphite precipitation more effectively than the in-stream inoculation process.
- The nodule count increased with increased inoculation percentage. At high cooling rates, the materials are more sensitive to this effect.
- The effect of nodule count and cooling rate (for heavy section castings) plays an important role in the determination of relative amount of ferrite and pearlite in the matrix.
- The effect of graphite nodularity on mechanical properties in as-cast condition has been investigated in the present study. The different degrees of graphite nodularity, from low graphite nodularity of about 67% to high graphite nodularity were produced by changing base compositional analysis and by adding different amount of spheroidizing (Mg) elements.
- With the increase in CE (for the melt no S1 to S5), the yield strength, impact strength, elongation increased whereas tensile strength and hardness decreased. This effect may be attributed to the effect of CE on graphite degeneracy. With the increase in CE, chunky graphite is formed in the melt during solidification and creates adverse effect on tensile strength and hardness.
- If the non –nodular graphite percentage increases in the matrix, it affects the tensile properties of SG iron castings.
- The minimum nodularity value of SG iron as per ASTM quality index graph may be considered ≥ 60% in order to get required properties for designing certain equipments.
- The study of the tensile properties showed that the yield strength and tensile strength are increased with increasing pearlite level in the matrix (Fig. 5.22f, fig.5.22g,

fig.5.32f and fig.5.32g) for the melts N1 to N5 and C1 to C5 respectively as compared to ferrite matrix (table 5.13).

- The impact strength is significantly influenced by matrix microstructure as observed in the present investigation (table 5.1b, 5.13, Fig.5.22i and Fig.5.32i).
- The Brinell hardness value is found to increase with increasing pearlite content of the matrix structure of the present material as investigated. It increases from about 126 for 92% ferrite matrix to about 252 as the matrix structure approaches to pearlite (33% pearlite). This change in hardness value affects the ductility and charpy impact strength of the material.
- For all the melts, the as-cast microstructure was ferritic-pearlitic and the nodularity exceeded around average 85%, in accordance with the ASTM A247 standard. The presence of nickel (melt no. N1 to N5) and copper (melt no. C1 to C5) promotes pearlite formation and stabilization which plays a vital role for property enhancement of SG iron castings.
- The amount and morphology of the ferrite present in the final microstructure depend on the melt chemistry (melt no. S1 to S5), The CE and Si accelerate this process. But CE $\geq$ 4.8% and Si $\geq$ 2.8% are not recommended for the production of ductile iron castings due to their detrimental effects on mechanical properties.
- The high ductility of ferrite matrix (melt no.S5) of the thick-walled ductile iron casting (20.2%) reflects its ability for considerable deformation before fracture takes place whereas the material with low ductility (melt no. C5) SG iron (6.2%) with pearlite (33%) an unforeseen load may cause failure.
- Presence of alloying elements like Ni & Cu are beneficial to the ductile iron production but addition percentage to be strictly controlled due to their deleterious effects on the as-cast thick-walled castings.

- The three grades of DI which were produced in this investigation are good candidate for applications as per recommendations. The best combination in chemical composition for achieving desired mechanical properties in as-cast condition for heavy section DI as per applications requirement may follow the melt chemistry of S3, N5 or C5.
- The present investigation makes clear that with an appropriate balance/ controlling of alloying elements (Ni & Cu), microstructure and mechanical properties may be achieved and heat treatment process can be avoided.

Scope for Future Work

The present research work leaves a wide scope of work for future investigators to explore many other aspects of production of thick-walled Spheroidal Graphite iron casting and its property characterization. Based on the findings in the present investigation, some recommendations for future research include:

1. More research & development work in the production of as-cast heavy section ductile iron castings used for wind mill parts.
2. Study of effect of dross and slag on surface appearance & fatigue endurance for the production of heavy section ductile iron castings.
3. Since the mechanical properties of spheroidal graphite iron depends on the controlled microstructure, then study of processing parameters on the production of thick-walled ductile iron is of great importance.
4. Study of the effect of addition of rare earth elements like cerium in different wt% on nodule count and nodularity of ductile iron.
5. Study of addition of Nickel in higher wt% in the production of as-cast heavy section ductile iron casting and its property characterization followed by graphite morphology.
6. Study of role of Copper addition at higher level is of interest in understanding, how it can act as a pearlite promoter.
7. Study of interlamellar spacing in pearlite and its impact on the mechanical properties of thick-walled ductile iron castings.
8. Fractography study in thick-walled SG iron castings.

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